3   Water Conservation and Efficient Use

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On the 200th anniversary of T.R. Malthus' famous *Essay on the Principle of Population*, Lloyd Evans (1998), the distinguished plant physiologist, explored the historical relationship between world population growth and food supply. Evans recounted the dire predictions of famous doomsayers and the remarkable technological revolutions in agriculture that have allowed us, at least thus far, to avoid being "checked," to use the Malthusian euphemism for mass starvation. And yet the world's population continues to grow, especially in underdeveloped nparts of the world, at rates that must disturb even the most buoyant optimist.

During the next several decades, dryland agriculture will play an increasingly important role in our efforts to maintain global food security. This is due to two relatively recent developments. The first is that, until about 1960, most increases in the world's food supply resulted from increasing the amount of land under production. Since then, most of the increasing demand for food in the world has been met by increasing yields. Additional lands still remain that could be brought into production, but as Evans (1998) pointed out, they tend to be unproductive, environmentally sensitive, remote, or otherwise unsuitable for agriculture. Indeed, many have argued that one of the most important reasons for continued yield increase is the need to protect environmentally sensitive land, including wildlife habitat. Furthermore, in many developed regions, including the USA, existing agricultural lands are gradually being lost due to such processes as erosion, salinization, urbanization (or "suburbanization"), and contamination.

The second, and perhaps more alarming development, is that the world's supply of fresh water for irrigation is limited and increasingly the object of competition. Irrigated agricultural land, which constitutes less than one-fifth of the

world's arable land, has been the largest source of global yield increase for wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), and other staple crops. Although there is now relatively little additional land left that is suitable for irrigation, a greater constraint in many regions is the availability of water for irrigation (Rothfeder, 2001). Also, many large aquifers in the world already, have been depleted to the point that remaining amounts of water are insufficient, or pumping costs too great, for farmers to economically produce low value, bulk commodity crops. The world's most populous countries, China and India, are both depleting aquifers at alarming rates to feed their burgeoning populations. How, one must ask, are they to feed those populations when irrigation cannot keep pace with water demand?

Competition for limited fresh water is becoming an increasingly important political issue among nations, segments of society, geographical regions, and seemingly disparate causes, including the environment, agriculture, industry, and urban development. This is especially so in arid parts of the world, where water is naturally in short supply, and the growing needs of industry and urban populations are already clashing with those of agriculture (Rothfeder, 2001). In most parts of the world, and especially in developed industrial countries, urban populations generally have greater financial and political wherewithal than do rural populations.

Barring major technological innovations such as the economic conversion of salt water to freshwater, or social developments such as reduced population growth in developing countries, the sustained trends of increased population, decreased land availability, and increased competition for limited fresh water resources lead to an inescapable conclusion so far as agriculture and food security are concerned: the burden of meeting food demand, while protecting environmentally sensitive lands from agricultural expansion, will fall increasingly on dryland agriculture. To meet this challenge, dryland cropping systems in developed and developing countries alike must use precipitation as efficiently as possible for food production. To realize increased efficiency requires an understanding of how crop production is related to such determining factors as precipitation and evaporative demand, water capture, water retention, and crop management.

Precipitation and Atmospheric Evaporative Demand

Water is essential for the establishment, growth, and reproduction of terrestrial crops. Frequent precipitation (P) usually provides adequate water for crops in humid regions, except during droughts. Precipitation becomes increasingly limited and erratic when going from humid regions to subhumid, semiarid, and arid regions. Ratios of P to potential evapotranspiration (PET, potential evaporation and transpiration) (P/PET) are >0.65, <0.50 to <0.65, 0.20 to <0.50, 0.05 to <0.20 and 0.05 in humid, dry subhumid, semiarid, arid, and hyperarid regions, respectively (UNEP, 1992). These ratios serve as a crude guide for classifying different regions (FAO, 1993) because P, soil water storage patterns, and length of growing season vary widely among sites having similar classifications (Fig. 3–1). All locations for which data are shown in Fig. 3–1 are classified as semiarid. On average, however, P at Bushland, TX, is less than PET each month, but is in
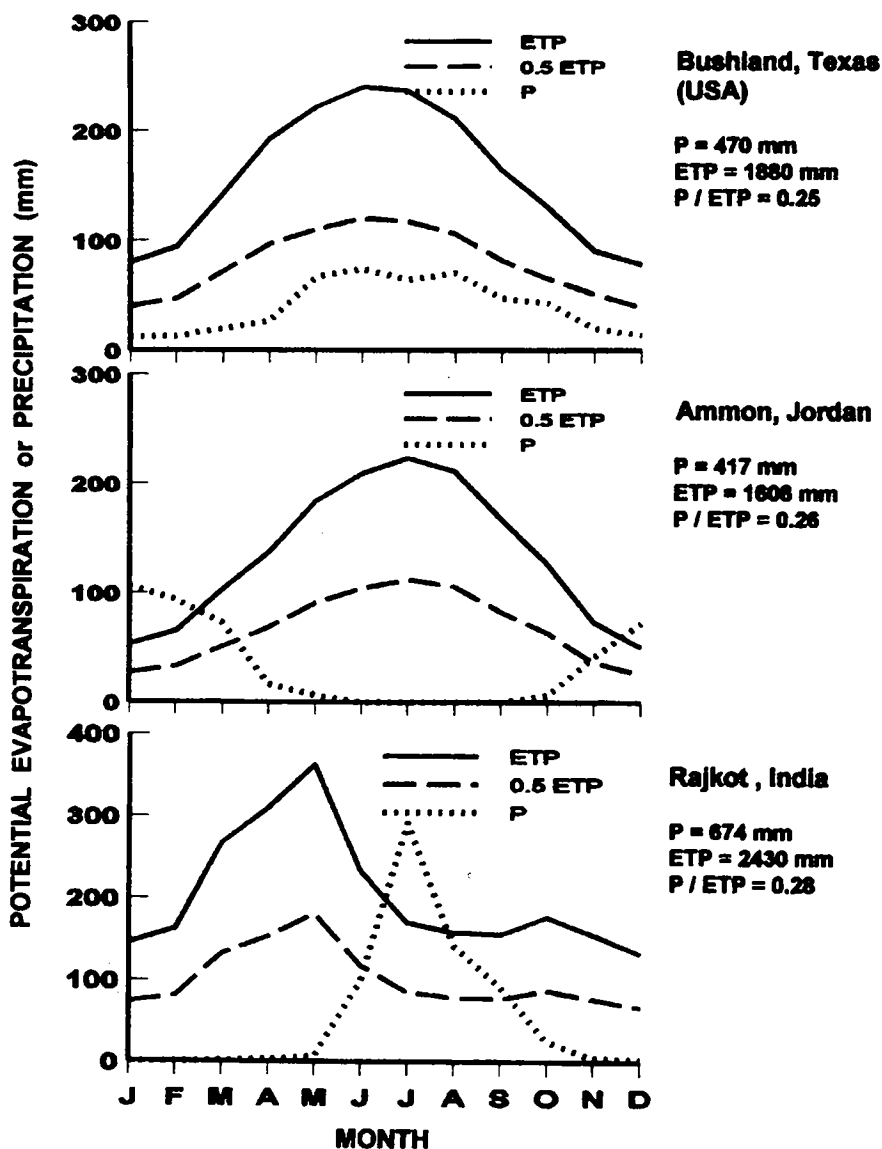
Fig. 3–1. Agroclimatic characteristics (potential evapotranspiration [PET] and precipitation [P]) of three representative dryland locations (adapted from Stewart, 1988).

excess of PET some months at Amman, Jordan, and at Rajkat, India. These examples illustrate that different management practices may be needed for successful dryland crop production, even within areas classified in the same category.

Some crops in subhumid and semiarid regions and most crops in arid regions are irrigated. Whether under dryland or irrigated conditions, successful crop

production depends on storing adequate soil water to sustain the crop until the next precipitation or irrigation event, except when water is applied frequently using a drip or sprinkler irrigation system. Even with irrigation, water conservation is important because of the increasing competition for water among agricultural, urban, industrial, and recreational users (Unger and Howell, 1999). While conservation may be important with irrigation, water can be applied to irrigated crops when needed. In contrast, dryland crops depend solely on stored soil water between precipitation events. Because of unreliable precipitation in drier regions, soil water storage is of critical importance for dryland crop production.

Principles regarding water conservation for successful crop production are the same whether a crop is grown under dryland or irrigated conditions, but we discuss them primarily for dryland crop production. These principles are that water must be captured, retained for later use by crops, and used efficiently for the production of marketable yield. Scientists have recognized these three principles for many years, but only recently have we had the technology to significantly change how we manage precipitation in dryland farming. Shaw (1911) and Widtsoe (1920), for example, recognized the need to capture, retain, and efficiently use precipitation before 1912. Unfortunately, the primary means of managing water in their time was via tillage. Shaw (1911), for example, stated "The dominant idea in dry farming is in a sense two-fold. It seeks to secure to the greatest extent practicable the conservation and also the accumulation of moisture in the soil. To accomplish this end, the soil is stirred deeply, whether by the aid of the plow alone or by following the plow with the subsoiler, or by using some other implement, as the deep tilling machine. The ground is compressed subsequent to plowing, and a dust mulch is maintained on the surface. The increase of organic matter in the soil is also sought."

Widtsoe (1920) believed that water retention via dust mulching was the most important issue in dry farming, followed by its efficient use. However, he was not able to effectively address water capture with the technology available to him. Shaw's (1911) solution to water capture and retention seemed to be more and deeper plowing, believing that it would increase storage capacity of the soil. These pioneers had little concept of residue retention and soil protection, and their recommendations often left the soil vulnerable to extensive erosion. Today, we know that intensive tillage has many adverse effects on the soil itself and, in fact, is inconsistent with the goal of increasing soil organic matter. Also, residue retention via reduced and no-tillage technology allows us to more effectively and simultaneously address water capture and retention, as well as soil conservation. In most cases, when reduced- and no-tillage systems are properly managed, they result in more sustainable dryland farming.

Water conservation management can interact with other components of the cropping system such as, for example, soil temperature. The use of crop residues to control evaporation, for example, affects transfer and storage of heat within the soil, plant canopy, and atmosphere, and can, therefore, also effect soil temperature and other micro-climate properties.

WATER CAPTURE

The first water conservation step in dryland agroecosystems is capturing the incident precipitation, whether it be rain or snow. It is critical to system sustainability that capture be maximized within the economic constraints of the particular situation. In this section, we focus on principles governing soil properties that affect water capture, like soil texture, aggregation, and pore size. We also explore the interaction of water capture and water retention against evaporation. For example, reducing ponding time at the soil surface and moving water rapidly below the surface reduces the opportunity for evaporation. This is especially important in areas with summer precipitation, where high evaporation potential follows the rainfall event, but it also can be advantageous in areas with winter precipitation because evaporation is an important factor even at cold temperatures under certain atmospheric conditions.

Principles of Water Infiltration

Water entry into soils appears, at first glance, to be a relatively simple process with the entering water simply displacing soil air. It is, however, a complex process that involves both saturated and unsaturated water flow. Unsaturated flow is driven primarily by the attraction of water to dry solid surfaces (adsorption) and the surface tension of water held between the solids, in the form of menisci, within the pore spaces that exist between solid particles (capillarity). Together, adsorption and capillarity produce the matric potential energy state of water. Additionally, unsaturated flow is affected by other forces as, for example, those caused by gravity or the presence of solutes (Hillel, 1998). In general, as long as precipitation intensity is below the saturated flow rate of the soil surface layer and/or there is no water ponding, water intake will be governed by unsaturated flow. As soon as the water application rate exceeds the soil's unsaturated intake rate, saturated flow becomes the dominant process. Unless the soil is coarse textured or the precipitation event is extremely short or of low intensity, saturated flow is the dominant mechanism of infiltration (Baver, 1956).

The rate of water entry under saturated conditions, the so-called infiltration rate, is controlled by surface soil porosity, soil water content, and soil profile permeability. Water capture is a complex issue because the maximum infiltration rate occurs at the beginning of a rainfall event and then decreases rapidly as water fills the surface pore space. If the soil is dry, there is a large storage capacity and a large potential energy gradient at the wetting front relative to the same soil in a uniformly moist condition; hence, water will flow rapidly into the soil (Taylor and Ashcroft, 1972).

Soil properties that affect the water infiltration rate in a given landscape differ for reasons that are not subject to management, like soil texture. Large amounts of surface soil macroporosity are needed to maximize water infiltration and this soil characteristic is highly governed by soil texture. Fine-textured soils generally have less macropore space and, consequently, lower infiltration rates

than coarse-textured soils. An exception would be highly-structured or cracked soils.

Aggregation also greatly affects a soil's macropore space. Thus, soils of the same texture, but with different degrees of aggregation, may differ greatly in amount of macropore space. In contrast to soil texture, degree of aggregation is susceptible to soil management. Adding organic matter to a soil, along with its oxidation, and tillage practices can all be used to modify soil aggregation.

Structural stability also alters the infiltration rate. Soils with weak structure quickly lose their ability to absorb water as the surface aggregates disintegrate and surface pore spaces become smaller. This can occur on wetting, from impact of raindrops, or exposure to saline water.

Several empirical equations have been proposed to describe infiltration; many were reviewed by Hillel (1998). For a uniform soil of constant initial wetness, infiltration can be described mathematically by Philip's (1969) solution,

$$i = S't^{1/2} + A't \qquad [1]$$

where i represents quantity of water infiltrated, which is a function of sorptivity (S'); the ability of the profile to transmit water (A'); and time (t). The parameter S' depends on the initial and saturated water contents of the soil. It is governed by surface soil properties such as texture, degree of aggregation, and aggregate stability. Because S' combines both conductivity and matric suction into one parameter, it is the dominant parameter governing the early stages of infiltration, which is of great importance to water capture in dryland systems. Soil water content at the beginning of a precipitation event modifies the effects of other properties because, as the initial water content increases, S' decreases. The parameter A' is controlled by subsurface soil properties and becomes progressively more important with time of infiltration. Under conditions of sustained infiltration, it asymptotically approaches saturated hydraulic conductivity, and eventually becomes the only significant parameter in the equation (Taylor and Ashcroft, 1972). But this commonly is not the norm in dryland systems.

Time (t) is a modifying factor for both S' and A' as is readily evident in Eq. [1]. Increasing the opportunity time for either S' or A' can be an excellent water capture enhancing technique. We discuss several soil management techniques that increase t at a later point in the chapter.

In dryland systems, management is focused mostly on soil properties that govern S' because these alter the ability to capture precipitation. Soil properties that control S' and that can be affected by management include structural configuration and aggregate strength and protection. The immediate soil surface, the water-soil contact interface, is the point of focus because, as first emphasized by Horton (1933), conditions at the soil surface mainly govern the infiltration rate. A subsequent historical review of this topic was given by Parr and Bertrand (1960).

The goal in dryland soil management is to use practices that maximize S' in a realistic and economic manner within a given cropping system. To the extent permitted by the dryland environment, we can also manage the opportunity time, t, in our approaches to water capture.

Soil Cover Management and Water Capture

Soil cover management is a key agent in managing water capture in dryland systems. Tillage choices have been the primary means of cover management in cropping systems for centuries. New scenarios for cover management have evolved with the advent of herbicidal weed control that permit us to greatly improve the potential for water capture via residue retention.

Soil Cover Dynamics

Soil cover is defined as the sum of canopy cover and crop residue cover. Obviously, soil cover is highly dynamic and can range from 0 to 100%, all within a growing cycle of a crop, depending on the crop being grown and the tillage system being used. At crop planting, for example, soil cover consists only of the residue component. As the plant develops, cover becomes increasingly dominated by the plant canopy. While the canopy is developing, the residue component usually is declining as microbial decomposition and physical deterioration occur. As the crop senesces, residues once again become the primary soil cover. Cultivation management during and after the crop growth period also influences the total cover at a given point in the cycle.

Soil cover influences the S' parameter in Eq. [1] via raindrop energy absorption. Raindrop energy negatively impacts surface soil structure by causing soil particles to "slake" from aggregates, thus leading to their destruction. This decreases surface macropore space and ultimately decreases S' in a given soil system. The effect of raindrop impact on a bare soil can be severe because of the kinetic energy exerted on the aggregates, as calculated from mass and velocity of raindrops. The severity of raindrop impact on soil slaking is also determined by angle of impact, roughness of the surface, presence of ponded water, and structure and water content of the soil. Because soil water content affects aggregate slaking, the effect of raindrop impact is greatest at the beginning of the rainfall event.

The energy imparted to the soil surface during a rain event causes aggregate destruction, and whether soil aggregates withstand the impact depends in part on the relative mass of the drops and aggregates. Drop sizes vary depending on storm intensity, which in turn is determined by the climate of the given geographic region. Raindrop diameters range from 0.25 to 6 mm with a median value of about 3 mm, while aggregates in a cultivated soil often are <1-mm diameter. When a 3-mm diameter raindrop, falling at a terminal velocity of 750 cm s^{-1}, strikes a <1-mm diameter aggregate, the damage can be severe. Wind driven rain, which has increased raindrop velocity, creates greater impact according to Troeh et al. (1991), who supplied evidence by Lyles (1977) that wind-enhanced raindrop impact energy is as much as 2.75 times greater than in still air. For many soils, surface porosity is immediately decreased and S' is decreased on raindrop impact, which, in many instances, causes soil crusting and S' approaches 0.

When crusting occurs, tillage is needed to break the crust, thus allowing water from the next precipitation event to infiltrate. Tillage, however, increases the evaporation rate by exposing moist soil to the dry atmosphere, thereby causing

a net water loss. Therefore, it is best to avoid crust formation, if possible, thereby eliminating the need for tillage. Crusting is avoided by protecting the soil surface with residues and/or crop canopy cover.

Brengle (1982) summarized the falling drop force as one that impacts the soil aggregate in a downward, sideward, and upward manner. The downward force compacts and reduces pore size and, hence, infiltration, while sideward and upward forces create "soil splash." The combined forces break soil aggregates, dislodge aggregate fragments that are splashed about, and eventually plug remaining soil pores; the end result is decreased S'. Both crop canopy and crop residues can absorb this energy and decrease damage to soil aggregates.

Canopy Effects

It was reported as early as 1890 that plant canopy intercepted up to 45% of the raindrops (Troeh et al., 1991). When the canopy intercepts the water, it absorbs the drop energy and the water drips to the soil surface with greatly reduced impact, and soil aggregates undergo less damage, surface soil pores remain open, and S' is maintained at suitable levels.

As leaf area index increases during the growing season, it increases ground cover and decreases the raindrop energy impact on the soil surface, and S' thus is maintained at an acceptable level. Benefits in water capture resulting from canopy development are greatest in areas with summer precipitation; for example, corn (*Zea mays* L.) or grain sorghum [*Sorghum bicolor* (L.) Moench] production cycles in the Great Plains of North America occur during a period when 75% of the annual precipitation is received. In contrast, dryland areas that receive primarily low-intensity winter precipitation, like the Pacific Northwest in the USA, do not have active canopy development during the period when most of the precipitation is received. Nonetheless, early establishment of fall-sown crops to obtain partial soil cover is recognized as an important deterrent to soil detachment and runoff during winter months.

Residue Effects

Crop residues have many roles in dryland agriculture, including protection against erosion by wind and water, protection of aggregates, and decreasing soil water evaporation. But they also have competing economic roles to play such as providing animal fodder and fuel for food preparation. In some situations, too much residue can interfere with planting and other field operations. Obviously, these roles are not independent of the others, but we concentrate on residue effects on precipitation capture in this section.

Residues impact both S' and t in Eq. [1]. Sorptivity (S') is affected because the residues absorb raindrop energy, which keeps soil aggregates from being destroyed and, in turn, keeps surface soil pores open for water entry. When available in sufficient amounts, residues affect t, first by physically blocking water runoff, and second by slowing evaporation after a rain event, thus allowing water to move into the profile before being vaporized. The water and energy balances of residue-covered soils constitute complex processes, however, and the amount of water conserved by residues varies with specific circumstances (Papendick and

Campbell, 1988). Indeed, it is possible for water losses due to evaporation to be greater with the addition of crop residues because the soil surface remains wet longer.

Duley and Russel (1939) were among the first to recognize the benefits of soil protection via crop residues. For example, in one of their 1938 experiments at Lincoln, NE, they compared the effect of a 4.5 Mg ha^{-1} flat straw cover with an equal amount of incorporated straw and with a bare cultivated surface on water conservation. Water conserved amounted to 54% of the rainfall for the flat straw covered surface treatment as compared with 34% when incorporated and only 20% with a bare surface treatment. Their experiment was not designed to separate the residue effects into its protection, evaporation, and water-blocking components, but their comments indicated that maintenance of surface porosity and physical blocking greatly decreased runoff from rainstorms and were major contributors to enhanced season-long water capture. In related studies, surface soil condition (cover and aggregate size) was found to have a greater effect on water infiltration than surface soil texture or soil profile characteristics (Duley and Kelly, 1939).

The relative value of residues as a soil aggregate protector, versus its value as a reducer of overland flow, was addressed by Borst and Woodburn (1942) in a unique experiment where residues were suspended on a screen 25 mm above the soil surface and compared with the same amount of residues placed directly on the soil. Cultivated, dry, uncovered soil had runoff equal to 78% of the applied water, while soil in the same condition with 4 Mg ha^{-1} of residues on the surface had runoff equal to 1.7%. Equally low amounts of runoff, 1.2% of the applied water, resulted when the same amount of residues was suspended on the screen above the soil. They concluded that elimination of raindrop impact on soil aggregates was the major contribution of residues and that physical blocking of water flow across the surface played a minor role.

Data from Mannering and Meyer (1963) in Indiana, provide a clear demonstration of the protective mechanism of crop residues on water infiltration rates on Wea silt loam (fine-loamy, mixed, active, mesic Typic Argiudoll) with a 5% slope (Table 3–1). After four simulated rainfall events within a 48-h period, three being wet runs, the 2.2-Mg ha^{-1} residue rate still had a final infiltration rate near the initial rate. They reported that the straw mulch intercepted raindrops and dissipated their energy, thus preventing surface sealing. Under their conditions,

Table 3–1. Final infiltration rates from four simulated rainfall events on a Wea silt loam soil with 5% slope (adapted from Mannering and Meyer, 1963).

Straw rate		Initial infiltration rate	Final infiltration rate for wet runs		
			Wet 1	Wet 2	Wet 3
Mg ha^{-1}	Percentage cover	mm h^{-1}		mm h^{-1}	
0	0	38	23	23	23
0.55	40	41	23	15	20
1.1	60	58	43	25	20
2.2	87	64	61	53	53
4.5	98	64	64	64	58
9	100	64	64	64	61

Table 3–2. Water infiltration (rainfall simulation; 76 mm event) as affected by soil cover in two phases of a wheat-fallow cropping system with no contouring (adapted from Dickey et al., 1983).

Cropping system phase	Tillage system	Cover	Infiltration†	
			Total	% of rainfall
		%	mm	%
Fallow after tillage	Plow	4	31	41
	Stubble-mulch	92	74	97
	No-tillage	96	75	99
Wheat plants at 10 cm height in	Plow	26	32	42
spring of crop year	Stubble-mulch	38	50	66
	No-tillage	85	72	95

† Infiltration = 26 + 0.52 (% cover); r^2 = 0.96.

straw mulch effectiveness was highly correlated to surface cover, and coverage >85% was needed to maintain final infiltration rate at initial levels.

Dickey et al. (1983), using rainfall simulation on Alliance silt loam (fine-silty, mixed, superactive, mesic, Aridic Argiustoll) in western Nebraska, evaluated the effects of tillage on residue cover, soil erosion, and water runoff in four different phases of a wheat-fallow cropping system. We interpreted their data in terms of water infiltration as affected by cover in Table 3–2. Cover during the fallow portion was residues only, whereas during the spring early crop growth stage, cover was a combination of residues and short canopy. Note that increases in cover with less tillage and greater canopy greatly increased water infiltration, and there was a highly significant linear relationship between cover and water infiltration.

Logically, more cover should offer more protection and improve water capture as these data demonstrate. However, there are cases where increased residue cover has not improved water capture. For example, water capture on Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) at Bushland, TX, was not improved, even when residues provided up to a 68% cover (Unger, 1992a). The lowest residue levels after a grain sorghum crop, however, improved water capture when the soil was loosened with sweep tillage. In principle, residue cover protects soil surfaces against drop impact and resultant aggregate destruction, and should have the greatest potential for maintaining S'.

Interactive Effects of Residues on S' and Evaporation

The protective nature of residues enhances S' for the reasons described above, but it simultaneously affects the water evaporation rate, especially during evaporation Stages 1 and 2, as noted later in this chapter. Jones et al. (1994) reported an interesting interaction of infiltration and evaporation in a watershed study at Bushland, TX. They measured runoff and water storage during the fallow period of a wheat-grain sorghum-fallow cropping system, and compared minimum tillage with no-tillage management. Average runoff was greater with no-tillage than with minimum tillage by as much as 25 mm during the non-crop periods of the cropping system. This was because the crop residues did not provide adequate protection to prevent soil aggregate destruction and crusting with

the no-tillage system, while the surface pores were repeatedly reopened for water capture with the minimum tillage treatment. However, at wheat planting time, water content in the soil profile was 32 mm greater with no-tillage than with minimum tillage. At sorghum planting time, water content was 18-mm greater with no-tillage than with minimum tillage. Obviously, the water capture factor in water conservation cannot be considered independent of evaporation and, in this high evaporation environment, the evaporation component was equal to or greater than the water capture component. It is critical to consider the system in total because differences in evaporation potential, amounts and type of crop residue cover, and soil physical properties, including texture and aggregate stability, can all alter the net water storage outcome. For example, adding 25 Mg ha^{-1} of pearl millet (*Pennisetum* spp.) residues to sandy soils in West Africa did not improve water conservation due to a combination of rapid drainage and high evaporative demand (Payne et al., 1990). At Bushland, TX, however, a significant linear relationship between straw mulch cover and water stored during fallow occurred with each 1 Mg ha^{-1} of mulch resulting in an additional 5.6 mm of water storage during fallow (Unger, 1978). The improved water capture resulted from decreased evaporation and possibly greater infiltration as mulch rate increased (runoff was not reported).

Tillage Management and Water Capture

Tillage is practiced for reasons ranging from weed control to seedbed preparation, and often these operations influence soil water capture by their disruption of soil crusts and alterations in surface aggregate size distribution. Tillage operations are never independent of crop residue cover because even the most minimal soil disturbance tends to incorporate some residues, which decreases the cover on the soil surface.

Pore Size Adjustments

Most often tillage creates large open macropores at the soil surface that greatly increase sorptivity (S'). If soils have little cover, aggregate sizes decrease during rain events and S' decreases in proportion to the rainfall intensity and duration. An example of the dynamic effects of tillage on water capture (water infiltration) is shown in Table 3–3 (Burwell and Larson, 1969). Large surface pores created by moldboard plowing, as indicated by greater random roughness, greatly increased cumulative infiltration, but subsequent tillage operations like disking and harrowing for seedbed preparation quickly reduced random roughness and infiltration. Pore size decreases, indicated by decreased random roughness, that occurred with tillage operations after plowing had a greater influence on infiltration than did total porosity.

Obviously, tillage management choices can alter water capture, but they cannot be considered independently of tillage effects on residue cover. Ideally, a large amount of soil macroporosity, with at least 50% cover, should result in a high S' that is sustainable throughout a rainfall event. The Jones et al. (1994) experiment, discussed above, illustrated this principle where infiltration rates were

Table 3–3. Effect of tillage on cumulative infiltration and rainfall energy required to initiate runoff on a Barnes loam soil (fine-loamy, mixed, superactive, frigid Calcic Hapludoll) (adapted from Burwell and Larson, 1969).

Tillage	Pore space	Random roughness	Rainfall kinetic energy to runoff	Amount of infiltration before runoff occurred
	cm^3	cm	Mg m ha^{-1} mm of rainfall	cm
Untilled	8	0.6	8.1	0.9
Plowed (15 cm)	13.9	5.7	80.4	9.3
Plowed-disked-harrowed	10.6	1.5	21	2.4
Field cultivator (10 cm)	11.3	3.5	57.4	6.7
Rotary tilled (15 cm)	12.9	1.7	41.4	4.8

higher and runoff was lower with stubble-mulch tillage than with no-tillage management.

Aggregate Stability and Tillage Type

Soil aggregate stability impacts S' in terms of how long the surface pores remain open to water penetration during a rain event. Soil structure deteriorates with increasing tillage intensity and/or years of cultivation (Taylor and Ashcroft, 1972). Tillage has negative effects on soil aggregates for two main reasons: (i) physical grinding that reduces aggregate size and (ii) increased soil organic matter oxidation that occurs because of macroaggregate destruction and subsequent increased exposure of organic compounds to soil organisms. Aggregate size distributions also shift, such that microporosity increases at the expense of macroporosity, which results in decreased S'.

The degree to which tillage affects S' is governed by complex interactions of tillage type, climate (particularly rainfall and temperature), and time, along with an array of soil characteristics like texture, original structure, and organic matter content. Thus, long-term tillage of any soil decreases aggregate resistance to physical disruptions like raindrop impact and tillage operations of all sorts. However, both soil clay minerals, including iron and aluminum oxides, and organic matter stabilize soil aggregates and make them resistant to physical disruption. Kemper and Koch (1966) quantified their combined effects. Although other factors like exchangeable sodium and calcium carbonate content affect aggregate stability, clay and organic matter content are by far the primary ones. Kemper and Koch (1966) concluded that organic matter contents in excess of 2% (1.2% organic carbon, C) added little to aggregate stability, but that reduction of organic matter levels below 1% (0.6% organic C) caused rapid decreases in aggregate stability.

Of these two primary properties governing aggregation, only soil organic matter content can be affected by soil management options in any practical sense. The degree of practicality of even this changes according to conditions, because the soil organic matter level is largely determined by two rate-mediated processes: accumulation and decomposition. The first is determined mostly by amount of organic inputs, which is highly dependent on rainfall or irrigation amount. The second is determined mostly by temperature, which is often quite high in semiarid

environments. The objective of maintaining or increasing soil organic levels, therefore, is much more easily attainable in cool, moist environments than in hot, dry ones.

The "freshness" of organic matter compounds is critical to aggregate stability. In soil ecosystems, freshly added or partially decomposed plant residues and their humified turnover products, otherwise known as the young humic substances, constitute the "labile" organic matter pool. Older or more stable humic substances, which tend to be more resistant to further decomposition, constitute the "stable" organic matter pool. It is generally recognized that the labile soil organic matter pool regulates the nutrient supplying power of the soil, particularly nitrogen (N), whereas both the labile and stable pools affect soil physical properties such as aggregate formation and structural stability. Formation of the labile and stable pools is a dynamic process that is controlled by several factors, including the type and quantity of organic inputs, and their rates of decomposition and transformation.

In an early study, McCalla (1942) used aqueous suspensions from decayed wheat straw to study soil aggregate stabilization. He studied the effects of these suspensions on the water intake rate of a structure-less loessial soil parent material (14% sand, 66% silt, 20% clay, 0.2% organic matter) by incubating the material after incorporating the decayed wheat straw suspensions. He then measured the effects of simulated rainfall for a 3-h period. The nontreated material with only a surface straw application had an intake rate of 11 mm h^{-1}, compared with 68 mm h^{-1} for the material that received the aqueous suspension of decomposition products. In recent years, there has been renewed interest in organic matter constituents on soil aggregation and rapid gains have been made in our understanding of organic matter effects on soil structural stability (Beare et al., 1994; Six et al., 1998, 2000a, 2000b).

Although the effects of soil organic matter on soil structure differ with soil texture and mineralogy, specific information on these effects in tropical semiarid regions is scarce, and sometimes conflicting. This can be illustrated from reviews of studies on the effects of soil organic matter on soil structural development (De Datta and Hundal, 1984; Douglas and Goss, 1982; Krishnamoorthy and Kothandaraman, 1982; Lal and Kang, 1982). Accounts can be found of additions of farmyard manure, compost, or crop residues increasing structural stability of alluvial soils in northern India; of Ultisols in Puerto Rico; and of Alfisols in southwestern Nigeria. However, the structural effects of additions of large quantities of farmyard manure were negligible for sandy soils in Egypt and clayey Vertisols in India, which represent opposite extremes in terms of texture. As soil structure development is a long-term process, lack of improved structure in the sandy and clayey soils may also be partly due to the difference in amounts of organic matter added in the various experiments, and the lack of long-term data to facilitate meaningful comparisons. For sandy or kaolinitic soils, applications of compost up to 16 Mg ha^{-1} yr^{-1} were needed to improve soil structure (De Datta and Hundal, 1984). Unfortunately, such amounts are unrealistic in most agroecosystems.

A large interest has developed in determining how tillage affects soil structural development and maintenance in relation to soil organic matter content,

especially with the advent of no-tillage management. Soil scientists have used the pioneering work of Oades (1984) and Tisdale and Oades (1982) to develop an understanding of tillage and organic matter interactions in aggregate development and maintenance. It is generally accepted that increasing tillage intensity enhances soil organic matter losses and decreases soil aggregation. Beare et al. (1994), Elliott (1986), and Six et al. (1998, 2000a, 2000b) concluded that increasing cultivation intensity leads to a loss of C-rich macroaggregates and an increase in C-depleted microaggregates.

Tillage and Infiltration Opportunity Time

Cumulative infiltration is a function of opportunity time (t) as shown in Eq. [1], and increasing the time component is a key management tool in water capture. The basic principle for increasing opportunity time is to interrupt water flow, thereby slowing it and keeping it in contact with soil for a longer time. Contour cultivation, terracing, furrow-diking, and water spreading have all been used to improve opportunity time for infiltration (Troeh et al., 1991).

Contour cultivation produces ridges perpendicular to the slope and is most effective on <5% slopes. Contouring in a wheat-fallow system with plow tillage improved cumulative infiltration by 60% on a silt loam in western Nebraska (Dickey et al., 1983). With good residue cover, however, there was no difference in infiltration between contouring and slope tillage treatments when either stubble-mulch or no-tillage management was used. Contouring improved water capture even on soils with <0.5% slopes at Spur, TX (Fisher and Burnett, 1953). Averaged over 25 yr, water loss was 13.7% of annual precipitation without contouring and 9.7% with contouring. As a result, soil water storage was 20-mm greater with contouring, which subsequently increased cotton (*Gossypium hirsutum* L.) yields by 25%.

Ridge-forming tillage on the contour is rarely exactly on the contour and water will run in the furrows to some extent. Water conservation can be improved in these situations with furrow diking. Furrow diking apparently was first used in the USA in 1931 by a farmer in eastern Colorado (Chilcott, 1937), but little interest remained in the technique by 1950. Applications of furrow-diking re-started in the 1980s in Texas, as described in the brief history of furrow diking provided by Jones and Clark (1987). This same principle is used in the semiarid tropics of Africa on Alfisols where it is called tied-ridging. In that situation, it decreases runoff and erosion and sometimes increases yields, but in years with high rainfall or in years with protracted wet periods within the rainy season, yields decrease because the excess water does not drain away (El-Swaify et al., 1985). Effectiveness of furrow diking depends on soil, slope, rainfall, and how well a system is designed. According to the FAO (1993), ridging decreased erosion and runoff by 7 to 13% in West Africa. On clay soils, however, it may induce water-logging, and in severe storms, poorly designed systems can result in overflow of ridges and result in increased erosion.

In Texas, on soils with furrow slopes ranging from 0.1 to 0.4%, grain sorghum and cotton yields were 108 and 32% greater, respectively, for diked than for undiked conditions (Gerard et al., 1984). On a topographic basis, furrow

diking increased grain sorghum yield by 302, 140, and 42% compared to nondiked for upper, middle, and lower parts of the slope, respectively. For cotton on a coarser-textured soil, yield increases were 57, 37, and 11% for the same slope positions, respectively.

According to Clark and Jones (1981), 5-yr average grain sorghum yields were 1650 kg ha^{-1} with dikes compared with 1420 kg ha^{-1} without dikes, a 16% increase with dikes; water from storms up to 150 mm were retained on 1.0% slopes. Furrow dikes had their maximum benefits for within-season water capture for sorghum and on water storage during fallow. Benefits during the wheat-growing season were minimal because little runoff occurs during that period of the crop cycle. Furrow diking during the fallow period at Uvalde, TX, was critical to yield improvement, but diking only during the cropping season was not effective (Tewolde et al., 1993).

Baumhardt et al. (1993) studied water balance and yields of cotton and grain sorghum as affected by diking. No-tillage of sorghum residues increased total infiltration over either chisel-disk or disk tillage bare soil. Residues (3800 kg ha^{-1}) reduced crusting and sealing and maintained water infiltration. Diking reduced runoff from conventionally-tilled sorghum and cotton on relatively level soils about 50% of the time. No-tillage cotton after sorghum produced more lint than conventional tillage regardless of diking. They concluded that, although diking reduced runoff from nearly level soils, furrow dikes had limited potential to increase yields of crops. No-tillage of high residue crops was more effective than furrow dikes for increasing water conservation on nearly level semiarid soils. A similar conclusion was reached by Unger (1992b) who studied furrow diking in an irrigated-wheat (furrow irrigation)-dryland grain sorghum-fallow cropping system. On gentle slopes, furrow diking in combination with no-tillage and reduced tillage did not increase water storage or crop yield over no-tillage alone.

The reader is referred to Harris and Krishna (1989) for a historical perspective on furrow diking and specific information regarding machine types and costs of operation relative to potential gains. They summarized experiences with cotton, corn, and grain sorghum.

Terracing is much more expensive than contouring and diking of contour furrows and results in a permanent topographic change. Terraces can conserve water if designed for that purpose, but the usual graded terrace is an erosion control device, and is not designed to conserve water. There are two types of terraces specifically designed to conserve water, namely, level ridge-type and conservation bench. They not only slow or prevent water movement downslope, but also spread water, thereby increasing opportunity time for infiltration (Troeh et al., 1991). Level ridge-type terraces are best suited to situations with deep, permeable soils that have high water storage capacities and slopes <5% (Troeh et al., 1991). Conservation-bench terraces, in contrast to level ridge-type terraces, consist of a series of level benches separated from each other by unleveled, runoff-contributing areas (Troeh et al., 1991). The principle of the conservation-bench is to capture runoff from the unleveled portions of the field and spread it across the level benches to increase infiltration opportunity time. They were first developed for use in the U.S. Great Plains by Zingg and Hauser (1959). Cropping system management of the benches themselves is usually different from that used

for the water-contributing areas. For example, one might practice alternate crop-fallow on contributing areas and continual cropping on the level bench areas.

Hauser and Cox (1962) compared conservation-bench terraces with level and graded terraces in a 3-yr period at Bushland, TX. Grain yields were 1.67 Mg ha^{-1} with the conservation-bench system, 1.14 Mg ha^{-1} with level terraces, and only 1.09 Mg ha^{-1} graded terraces. In the U.S. northern Great Plains, conservation bench terraces were effective for collecting snow, capturing snowmelt and torrential rain runoff, reducing erosion, and increasing yields through water conservation (Haas et al., 1966). They concluded that a contributing area to level bench ratio of >1:1 may be required to maximize benefits. Use of conservation bench terraces with a contributing area to level bench ratio of 2:1 increased soil water storage by 18 to 43 mm compared with nonbenched areas with subsequent increases in sorghum grain yield on the benches in the U.S. central Great Plains (Mickelson, 1968). According to Mickelson (1982), contributing area to level bench ratios >3:1 are suitable in the central Great Plains and ratios as high as 7:1 are potentially feasible.

Jones and Shipley (1975) made economic comparisons of conservation bench terracing with bench terraces that had no contributing area and concluded that using conservation benches was more profitable because construction costs were lower and overall productivity was higher. The contributing areas between the conservation benches are not leveled so fewer terraces are needed on a given land area, which decreases construction costs. In addition, the increased water storage on the conservation benches made it possible to increase cropping intensity on the benches, which increased average annual yields on a field basis and thus net income. Despite the sound principles and the positive research results, few producers use this conservation system. Perhaps the initial investment costs, more intensive management requirement, and disruption in whole field operations have discouraged their adoption. Also, the use of conservation tillage (especially no-tillage) is less costly and is highly effective for controlling erosion.

Water Harvesting

Water "harvesting" has been used since ancient times in dryland cropping systems to collect and store water within a field or from adjacent areas for later use to meet patterns of crop water demand. Although the principle is fairly simple, the various techniques used to collect and store water are quite varied, and depend on several climate, crop, soil, and watershed factors. Water harvesting is an extension of the principles used with the conservation-bench terrace. Inhabitants of arid areas have used water-harvesting techniques for millennia. The principle is to cause S' to be near zero in a water contributing area and to catch the runoff water in a structure of dams or cisterns. The captured water can then be applied to crops grown on better soils at the discretion of the manager farmer. The objectives for water harvesting are varied in approach and scale. The approach may range from capture of rainfall in micro-catchments to harvesting of dew or snowmelt. The scale can range from harvesting runoff from roofs and courtyards for use in small gardens to elaborate ground catchment systems over large watersheds. The common elements are a catchment basin, conveyance device, storage

facility, and cultivated field (Perrier, 1988). Options differ in cost, required skills, and labor required. Perrier (1988) cautioned that it becomes easy to confuse what is technologically possible with what is economically and culturally possible.

Evenari et al. (1971) provided a fascinating history of water harvesting in the Negev region of Israel and their experiences in restoring an ancient water-harvesting project. They demonstrated that areas with only 150 mm of annual precipitation can support a civilization with water-harvesting techniques. According to Evenari et al. (1968) and Cohen et al. (1968), 1 ha of land receiving runoff from a 20- to 30-ha hillside area can sustain fruit tree production.

Harvested water is of high value in dry environments because of water scarcity and because of the low cost of water harvesting. Consequently, it is most often used for production of high-value crops like trees, fruits, and vegetables. For example, Kowsar et al. (1978) and Mehdizadeh et al. (1978) studied water harvesting to supplement water supplies for green belts in Tehran, Iran. They used asphalt covers on the contributing areas to encourage runoff and found initial runoff efficiencies of 75%. Tree growth was improved by using the runoff water, but sustainability of the asphalt layer was a problem because freeze-thaw action ruptured it, and its effectiveness decreased to 25% after 4 yr.

More recently, Cook et al. (2000) discussed how rainwater harvesting is of increasing interest in the Gansu Province of the People's Republic of China. They propose to store runoff water in tanks and use it for drip irrigation to maximize production per unit of stored water. They hope to demonstrate that by using rainwater efficiently, they can alter land use practices and increase net income in selected rural areas.

Disruption of Zones (Layers) in the Soil Profile that Impede Water Movement (A')

Soil profile properties also affect water infiltration and are represented by A' in Eq. [1]. Unlike S', soil profile characteristics governing A' generally are not alterable with practical soil tillage; for example, inherent soil clay pans cannot be significantly or at least only temporarily altered by tillage. Other management options can, in some cases, affect A'. For example, rotation with crops that possess deep taproots such as pigeon pea (*Cajanus cajan* Millsp.) or *Brassica* species can improve A'. In other situations, incorporation of large amounts of crop residues or green manure in fine-textured soils has increased macroporosity, which can positively affect soil physical properties such as infiltration rate and hydraulic conductivity. Lal et al. (1984), for example, demonstrated that using a rice straw mulch at a rate of 12 Mg ha^{-1} per season on a sandy kaolinitic Alfisol in Nigeria significantly increased soil macroporosity after 1 yr or two seasons of cropping.

Positive effects of "subsoiling" to alter A' have been observed on soils with genetic pans (pans created during pedogenesis) on Ultisols in the southeastern USA and on soils with manmade tillage pans. Campbell et al. (1974) reported that disruption of a compact A2 horizon with a chisel increased water capture by increasing infiltration rates and increased crop yield by allowing increased access to soil water as well as promoting additional water storage. Results in the U.S. Great Plains, where few genetic soil pans exist, have been much less encouraging.

Duley (1957) summarized 75 yr of Great Plains experience with subsoiling in a review paper as follows: "Much of the experimental work on subsoiling in the Great Plains was done during the early part of the century. The results obtained did not encourage further research. Neither did it encourage many farmers to subsoil. Subsoiling increases the power requirements and cost of preparing land, as compared with ordinary tillage. However, failure of most experiments to show profitable results did not dispel the idea that deep tillage or subsoiling somehow should be a good thing. For this reason a considerable amount of subsoiling has been done by farmers during the last 10 to 15 yr."

Interestingly enough, in the beginning of the 21st century, many dryland farmers continue to "deep chisel," the modern term for subsoiling, despite the fact that few experiments have shown that it appreciably improves either water capture or subsequent crop yields. Zuzel and Pikul (1987) are of the few who report a positive effect of chiseling on water infiltration that was sustained over the winter period. Two factors seem to be involved in the general lack of positive response to deep chiseling. First, shortly after the chisel has passed through the soil, the opening left by the chisel is closed at the surface by crumbling soil that is moved by wetting-drying phenomena, wind, gravity, or subsequent cultural operations. Once the opening is closed at the surface, the infiltration rate is again controlled by S'. Second, if the chisel mark remains open for substantial amounts of time, evaporation of soil water from the sidewalls of the open slot is large relative to that from unchiseled soil. As a result, there will be a net water loss from the soil because evaporation exceeds rainfall if it does not rain frequently.

Snow Capture and Melt Water Retention

A significant portion of dryland farming areas receive a part of their annual precipitation as snowfall. The initial step in maximizing the use of snow water is to obtain a basic understanding of snowfall facts for the geographic region of interest. For example, one needs information on snow amounts, storm size and duration, snow water content, and timing of snow events in relation to soil temperatures. The classic publication by Greb (1980) regarding snowfall in the U.S. central Great Plains provides an excellent example of how to characterize the snowfall potential of an area. He describes subjects ranging from how to measure snow water to efficiency of snowmelt capture in relation to snow timing. Once managers understand the snowfall characteristics for an area, they can begin to use snow capture principles that mesh with their particular cropping system.

Efficient capture of snow water has two features: (i) catching the snow itself and (ii) capturing the melted water. Because snow often is accompanied by wind, the principles of snow-catch are similar to the principles used in protecting soil against erosion by wind. Standing crop residue, shelter belts, strip cropping, and artificial barriers have all been used to maximize snow-catch. The basic principle of these devices is to create an area of decreased wind velocity on the downwind side of a barrier, resulting in the entrapment of snow particles behind the barrier. Barrier height and density affect size of the downwind protected area. Repeated barriers such as standing crop residues keep the wind profile above the surface

of the residues, and the captured snow remains inaccessible to future wind movement.

One of the most practical snow catch devices is maintenance of standing crop residues, as reported by Smika and Whitfield (1966), who showed that standing wheat stubble retained an average of 55 mm more water than bare soil at North Platte, NE. At Swift Current, AB, Canada, fields with standing stubble conserved 37% of the overwinter precipitation, while fallow fields with no standing residues conserved 9% (Staple et al., 1960). Soils in the stubble fields also were drier than the noncovered fallow fields, which encouraged water storage because there was more surface pore space available for immediate storage. In their situation, fall blade tillage to improve surface soil macropore space, but which flattened residues, had no positive benefits on soil water conservation in most years, which agrees with the findings of Power et al. (1958) in northeastern Montana.

The proportion of the land area covered by standing crop residues in a field obviously affects snow catch. In Colorado, Nielsen (1998) studied the effects of cutting height of sunflower (*Helianthus annuus* L.) stalks on snow catch and found a high correlation ($r^2 = 0.88$) between stored soil water from snow and residue silhouette factor, where the silhouette factor (Z) is calculated as:

$$Z = (H) - (0.01) (R)/(D) \qquad [2]$$

where H is stalk height, R is soil surface occupied by a stalk [(row spacing) (distance between stalks within a row)], and D is stalk diameter. Increasing H and/or R (plant population) increases Z and, in turn, increases the potential for snow capture.

Greb (1980) studied the use of vegetative barriers for snow catch and concluded that vegetative barriers having the following characteristics were most effective: (i) strong flexible stalks with good winter durability and >40-cm height, but not so tall or top heavy that wind or blowing snow would lodge the stalks; (ii) double-row instead of single row plantings to eliminate airflow gaps; (iii) stalk populations to provide 65 to 75% air porosity; (iv) spacings between barrier strips (the target area) of 11 to 19 m to accommodate common tillage equipment widths; and (v) parallel barriers oriented at right angles to prevailing winter winds.

The advent of no-tillage technology has made it possible to greatly improve snowfall catch with standing crop residues. Before the use of no-tillage, tillage operations necessary for weed control resulted in decreased proportions of standing residues and total residue cover, which minimized snow catch.

Snowfall capture remains the simplest part of capturing the snow water resource; capturing the snowmelt is far less predictable and manageable. For example, if the soil freezes before a snowfall event, there is less opportunity for water infiltration than if soils remain unfrozen. At northern latitudes, soils commonly freeze before the snowfall season begins. Furthermore, soil freezing depth depends on soil water content in the fall and on the insulative effects of the snow, which increases with snow depth (Willis et al., 1961). Dry soils freeze deeper and faster than wet soils, but frozen dry soils decrease runoff compared to wet

soils, provided the surface 30 to 35 cm are not wetted before the soil freezes (Willis et al., 1961).

The paradox of tall stubble to catch snow is that increased stubble height hastens the initiation of snowmelt, and decreases the amount of time required for complete melting of the snowpack (Willis et al., 1969). These authors suggested that standing straws: (i) conduct heat into the snowpack; (ii) intercept and absorb relatively more solar energy than snow; (iii) reflect solar energy onto the snow surface; and (iv) provide a heat trap against convection. Their overall conclusion was that the quantity of snowmelt runoff increases with increased stubble height for the same soil water condition, but that soil water levels in fall controlled the amount of water stored more than stubble height. They pointed out that "it is a paradox of nature that increased stubble height will trap and hold more snow, but runoff from the snowpack will also be greater." This means that the manager must be prepared to slow melt runoff with other techniques such as roughness and contours as discussed earlier in this chapter.

Maintenance of S' and water capture, when soils are frozen before snowfall and/or before winter rains, presents difficulties. Infiltration rates for frozen soils are determined by two factors: (i) soil frost structure, that is, small granulated units vs. massive concrete-like units and (ii) soil water content at the time of freezing (Zuzel and Pikul,1987). Soils frozen at low water content do not impede infiltration because they granulate, leaving adequate open pore space for infiltration. In contrast, soils frozen at high water contents freeze into dense, massive, concrete-like structures that are nearly impermeable to water (Zuzel and Pikul, 1987). Rapid warming accompanied by rainfall on such frozen soils can cause major runoff and erosion.

Climates like that of the Pacific Northwest in the USA present some of the greatest challenges in water capture because of their cold, humid winters (with frozen soils) and hot, dry summers. Furthermore, the topography is steep, which encourages runoff and gives little opportunity time for infiltration to occur. Research findings from this region will be used to demonstrate management techniques that maximize winter precipitation capture. Zuzel and Pikul (1987) found that fall chiseling before soil freezing enhanced cumulative infiltration both before and after freezing occurred. Final infiltration rates were 11, 6, and 16 mm h^{-1} in the fall, winter (soil frozen), and spring, respectively, in chiseled wheat stubble plots, and 7, 1, and 8 mm h^{-1} for the respective seasons in nonchiseled standing stubble plots.

Slot mulching is a technique of packing crop residues into, for example, 20-cm wide and 20- to 25-cm deep trenches, spaced at 2.5 m on the contour. The mulched slots are intended to create macroporosity at the surface that remains open during all seasons of the year, and especially during the frozen-soil period so that rainfall and snowmelt water can be captured. Saxton et al. (1981), working in the Pacific Northwest, reported that winter runoff was reduced from 114 mm in no-tillage, nonslotted wheat stubble areas to <10 mm in slot-mulched areas for the period from October through March. Their technique kept slots open for at least 12 mo after installation. Apparently, lack of efficient equipment seems to have limited adoption of this highly effective melt water conservation technique.

In eastern Oregon, soil ripping with a chisel, but without slot-mulching, increased the continuous macropore space at the soil surface, increased water infiltration rates, decreased erosion, and increased soil water storage compared with leaving the surfaces relatively smooth and unripped (Pikul et al., 1996). They cautioned that ripping a dry, pulverized soil was ineffective because loose soil fell back into the slot and sealed the ripper path.

The principle of increasing macroporosity to increase water capture on frozen soils has been used effectively in the fallow phases of wheat-fallow systems in geographic areas with winter precipitation. However, the potential for runoff and uncaptured water losses may be high in the crop phase of the system. Schillinger and Wilkins (1997) reported that increasing macroporosity by ripping in late fall to early winter after the wheat was well established, but before soil freezing, increased infiltration in a wheat-fallow system in the Pacific Northwest. Ripping decreased grain yield in the row most disturbed by the tillage shank, but it increased yield in adjacent rows; overall plot yields were not affected by ripping.

Winter precipitation capture can be maximized using the following principles: (i) catch snow with standing crop residues and (ii) maximize surface soil macroporosity during periods when soils are frozen.

Principles of Water Capture Synthesis

Favorable sorptivity (S') at the very surface of the soil and ample time for infiltration to occur are the keys to effective water capture. By far the most important principle in maintaining a favorable S' is protection of the soil surface from raindrop impact energy. Baver (1956) gave an excellent summary of maximizing water capture when he said, "When the transpiration effect on soil-moisture supply is combined with the interception of rainfall, decreased velocity of runoff, and increased soil porosity of the vegetation factor, the importance of protective vegetative cover becomes all the more significant. During the winter months in the temperate zone, when the large areas of leaf surface are not present to intercept the raindrops and to transpire water, vegetation (crop residue) functions primarily by decreasing the rate of runoff." Cover absorbs raindrop energy, protects aggregates, and maximizes surface macropore space, which slows runoff. Furthermore, during active plant growth, soil water content is kept low and that encourages infiltration.

WATER RETENTION

After water has been captured, it must be retained in soil for subsequent use by a crop. Successful retention involves reducing losses due to evaporation, use by weeds, and deep percolation, which we discuss in this section.

Evaporation Management

Water losses by evaporation prevent about 70% of the precipitation over land in the USA from moving into storage bodies (including the soil) or streams

(Hatfield et al., 1992). While much of the water evaporates before it is stored in soil, stored soil water also is subject to evaporation. Evaporation occurs both before a crop is planted and during a crop's growing season. Evaporative losses before planting are critical because they reduce the amount available for the ensuing crop.

In many dryland regions such as those having Mediterranean-type climates and in the U.S. Great Plains, production sometimes is forfeited during one or more growing seasons by keeping the soil surface devoid of vegetation. Such "bare" or "summer" fallowing is practiced to conserve a portion of 1 yr's rainfall for use by the next crop. Fallowing is commonly done in wheat-based cropping systems. Especially in dry or erratic rainfall environments, it serves to stabilize yield (Payne et al., 1997). In addition to increasing soil water storage, fallowing increases soil nitrate availability for the following crop because of increased oxidation, or break-down, of existing soil organic matter, and helps control weeds. Improved weed control results from using practices during the fallow period that are not possible during a crop's growing season. Using a rotation involving summer and winter crops is especially beneficial for achieving improved weed control. In this sense, it may be viewed as an efficient use of water. Although fallowing often is practiced to provide additional soil water for the ensuing crop and to stabilize yield, water storage efficiency during fallow (water stored as a percentage of rainfall received during the fallow period) often is low, especially when long fallow periods are involved (Jones and Popham, 1997). Storage efficiency depends on several factors, including soil physical properties and temporal patterns of rainfall and evaporative demand. Storage efficiency varies from as little as 0% on sandy soils in climates with high evaporative demand and summer rainfall patterns (Payne et al., 1990) to as much as 85% on silt loams in climates with relatively low evaporative demand and winter rainfall patterns (Haas et al., 1974).

In much of the U.S. Great Plains, storage efficiencies tend to be low. Storage efficiency was 11% for the dryland wheat–fallow (WF) system in the U.S. southern Great Plains. Length of fallow for the system is about 490 d (16 mo). For systems involving shorter fallow (between crop) periods, efficiencies were 14% for continual wheat (CW), 27% for continual grain sorghum (CS), and 17% for the winter wheat–fallow–grain sorghum (WSF) rotation (Jones and Popham, 1997). The percentages given occurred where stubble-mulch tillage was used; they were slightly higher where no-tillage was used. The between-crop periods are about 90 to 120 d for CW and about 240 d for CS. About 300 to 330 d of fallow occur between harvesting and planting of successive crops for the WSF system, which provides for one wheat and one sorghum crop during the 3-yr rotation. It has been estimated that using improved water conservation methods for annual cropping, including conservation tillage, would equal or surpass water storage benefits of summer fallow.

In contrast to precipitation before planting a crop, growing-season precipitation provides some water for immediate use by a crop. Some of the water, however, must be stored in soil to sustain the crop until the next precipitation event. Evaporation control during the growing season is important also because

water saved for transpiration rather than being lost by evaporation can significantly increase crop yields (Lascano et al., 1994; Payne, 1999).

Evaporation Stages

Soil water evaporation occurs in two (Ritchie, 1972) or three stages (Hillel, 1998; Lemon, 1956). Although these authors consider different numbers of stages, all agree the water losses are greatest in the first stage with falling rates in the subsequent stage(s). For our discussion, we use three stages of evaporation. First-stage evaporation depends on the net effect of environmental conditions (wind speed, temperature, relative humidity, and radiant energy) and water flow to the surface. Losses decrease rapidly during the second stage when water in soil decreases and the rate depends mainly on soil conditions that control water flow to the surface. During the third stage when water moves to the surface as vapor, the rate is low and controlled mainly by adsorptive forces at the solid-liquid interface (Hillel, 1998; Lemon, 1956). Greatest potentials for decreasing evaporation lie in the first two stages. Hillel (1998) states that evaporative flux can be modified in three basic ways: (i) by controlling the energy supply at the site of evaporation, for example, by modifying soil albedo through color changes; (ii) by reducing the potential gradient driving water upward through the profile, for example, by warming the surface layers so as to set up a downward-acting thermal gradient that restricts upward movement of water; and (iii) by deceasing the conductivity of the profile, particularly of the surface zone, for example, by tilling the soil. The effect of warming the soil surface on direction of water movement, however, would also depend on the vapor pressure gradients between the soil and the aboveground atmosphere. Overall, the best choice depends, among other things, on whether one intends to regulate first-stage evaporation, during which meteorological conditions dominate the rate, or second-stage evaporation, during which soil hydraulic properties become limiting.

Factors Affecting Evaporation

Soil water evaporation is a highly complex process. It involves water flow in soil in response to water potential differences, soil temperature gradients, and atmospheric conditions. Water potential differences occur between the atmosphere and the soil and within the soil itself. Evaporation is greatest when a soil is wet (high water potential) and the air is dry (low water potential; that is, low humidity or vapor pressure). The soil water potential changes constantly in response to decreases in water content due to evaporation, use by plants, or deep percolation, and increases due to precipitation. As a soil dries at the surface, water must flow to the surface to replenish that lost by evaporation. With continued evaporation, the flow distance increases, which results in increasingly slower flow to the surface as liquid or vapor and lower rates of evaporation. Eventually, water flow is only in the vapor phase, which results in even lower evaporation rates. These constantly changing water potential conditions result in constant changes in the water flow rate to the surface. The water potential of air also changes constantly due to climatic changes. Each water addition to soil, as by precipitation, restarts the evaporation cycle.

Another factor affecting water flow to the surface, and, hence, soil water evaporation, is the temperature gradient between the air and soil and within the soil itself. Because of the Charles-Boyles law, the vapor pressure of water increases with increases in temperatures. As a result, water vapor moves from warm to cool zones in soil, thus further contributing to the complexity of the evaporation process.

In addition to temperature, other atmospheric conditions influencing evaporation are solar radiation, humidity, and wind (Hatfield et al., 1992). Solar radiation provides the energy for evaporation, whereas air humidity and wind speed affect the vapor pressure gradient at the soil–atmosphere interface. High humidity and low wind speed result in a low vapor pressure gradient at the soil–atmosphere interface and, hence, a low evaporation rate. The potential for evaporation steadily increases with decreases in humidity and increases in wind speeds.

Many practices have been evaluated regarding their effect on soil water evaporation. Effective practices either form a barrier to prevent vapor movement from the soil, negate the energy available for evaporation, minimize the vapor pressure gradients at the soil–atmosphere interface, or disrupt water flow within the soil. These results are achieved by a mulch on the soil surface or by tilling the soil.

Mulch Effects

A mulch is "any material such as straw, sawdust, leaves, plastic film, loose soil, etc., that is spread or formed on the surface of the soil to protect the soil and/or plant roots from the effects of raindrops, soil crusting, freezing, evaporation, etc." (SSSA, 1997). We limit our discussion to the effects of straw (crop residues), plastic film (and related materials), and loose soil on soil water evaporation.

Crop residues are plant materials (straw, stover, stalks, leaves, cobs, etc.) remaining after harvest of a crop for its grain, lint, etc. These materials usually have little economic value and remain in fields after harvesting the crops. However, straw, stover, etc. sometimes are used as feed for animals, fuel, manufacturing, or shelter (Parra and Escobar, 1985; Powell and Unger, 1998; Unger, 1988). We recognize the use of residues for those purposes, but here discuss their value for controlling evaporation, thereby illustrating their potential for conserving water and improving crop production when they are used as a mulch on the soil surface.

Crop residue characteristics that affect evaporation are their orientation (standing, flat, or matted), which affects the thickness and porosity of the layer; layer uniformity; reflectivity, which affects the radiant energy balance at the surface; and the aerodynamic roughness resulting from the residues (Van Doren and Allmaras, 1978). Crop residues have been used as mulches in numerous studies, but their direct effect on soil water evaporation under field conditions has been difficult to measure. In the following studies, however, retaining crop residues as a mulch clearly decreased evaporation.

Smika (1983) in Colorado measured soil water losses that occurred during a 35-d period without precipitation. Loss was 23 mm from bare soil and 20 mm

with flat wheat residues, 19 mm with 75% flat and 25% standing residues, and 15 mm with 50% flat 50% standing residues on the surface. Residue amounts were 4.6 Mg ha^{-1} and standing residues were 0.46 m tall. Wind speed needed for water loss to begin increased as the amount of standing residues increased and the water loss rate decreased with increased amounts of standing residues at a given wind speed. Residue orientation also affected water losses through its effect on soil surface temperatures (47.8, 41.7, 39.6, and 32.2°C with the respective treatments) through their effect on the vapor pressure of soil water. Nielsen et al. (1997) showed that potential evaporation decreased as residue height increased. Height was especially important when stem populations were <215 m^{-2}, and the effect decreased with increasing stem populations.

At Akron, CO, Smika (1976) measured soil water contents 1 d after a 13.5-mm rain and again at 34 d without additional rain. Initial soil water contents were similar to a depth of 15 cm where conventional-, minimum-, or no-tillage treatments were imposed after harvesting winter wheat. The treatments resulted in surface residue amounts of 1.2, 2.2, and 2.7 Mg ha^{-1}, respectively. At 34 d, the soil water content was <0.1 m^3 m^{-3} to depths of 12 cm with conventional tillage and 9 cm with minimum tillage, the depths to which blade tillage was performed 8 d before the rain. In contrast, the soil had dried to the given water content only to a 5-cm depth where no-tillage was used. Some water was lost from greater depth with all treatments, but total water content was greatest with no-tillage for which the surface residue amount was greatest.

The value of crop residues for water conservation depends on several factors, including residue quantity, type, and placement; evaporation potential; fallow length; precipitation characteristics; tillage practices; and soil type (Papendick and Parr, 1989), as well as wind speed (Tanner and Shen, 1990). In many developing countries, because of competition for residues for other uses, it is questionable whether sufficiently high rates of mulch to reduce evaporation from the soil surface could be maintained. Residues are most effective for water conservation during the rainy season, when they reduce the amount of energy that arrives at the wet soil surface. After rains cease, evaporation losses from residue-covered soils can exceed those from bare soils if soil surfaces are wetter (Papendick and Parr, 1989). There are clearly situations in which mulching will not have any effect on soil water conservation, although there may be other beneficial effects such as temperature modification and erosion control. Mulching during the dry season in sandy soils of West Africa, for example, does not appear to be an effective technique for conserving soil water because of the low water-holding capacity of soils and deep drainage (Nicou and Chopart, 1976; Payne et al., 1990).

Probably the most commonly-used mulches that are not crop residues are plastic films, which are highly effective for controlling soil water evaporation. When Griffin et al. (1966) covered the soil with plastic to prevent evaporation and rain infiltration (100% cover) during the growing season of grain sorghum, grain yield was 6.27 Mg ha^{-1} using only 178 mm of water from the soil. On uncovered plots that were irrigated two times, grain yield was 5.82 Mg ha^{-1} and water use was 457 mm. With a 90% plastic cover on the surface, grain yields for corn planted on ridges in the U.S. northern Great Plains were 4.33 Mg ha^{-1} with 378 mm of water use in 1960 and 3.93 Mg ha^{-1} with 198 mm of water use in

1961. For the check treatment (not covered), yield was 3.2 Mg ha^{-1} and water use was 404 mm in 1960. In 1961, yield was 1.62 Mg ha^{-1} and water use was 160 mm for the check treatment (Willis et al., 1963). Clearly, controlling evaporation with plastic films is effective for conserving water for improved crop production.

Plastic films are used extensively for crops in some countries. In the People's Republic of China, for example, transparent plastic sheets 0.005- to 0.007-mm thick are widely used to cover the soil before or after planting a crop in early spring. Almost no evaporation occurs from the covered soil, thus conserving soil water for germination and seedling establishment. A hole is made in the sheet through which the plants grow. In northern China, soil temperatures under the plastic were higher by 2 to 6°C on clear days, 1.2 to 2.3°C on cloudy days, and 1.0 to 2.5°C on rainy days than in uncovered fields. The improved soil water and temperature conditions resulted in earlier crop planting and maturity, which improved farmers' incomes. Use of the plastic covers increased corn yields from 44 to 165% (Ma, 1988). In Shanxi Province in China, grain yields were 65% greater (average 4.15 Mg ha^{-1}) when dryland wheat was planted on three rows in 30-cm wide furrows separated by 30-cm wide ridges covered by plastic films than when grown conventionally (planted without the plastic cover). The increase was attributed to improved water conservation, namely, improved water supply to the plants and evaporation reduction. Equipment is available to form the ridges and furrows, apply the plastic cover, and plant and fertilize the crop in one operation (Yang et al., 2000).

Tillage Effects

Results of the foregoing studies clearly show that crop residues retained as a mulch on the soil surface can reduce soil water evaporation and thereby conserve water for crop use. The evaporation reductions resulted primarily from reduced turbulent transfer of water vapor to the atmosphere. A major limitation to using residues as a mulch under dryland conditions is that the crops often do not produce enough residues to have a significant effect on evaporation. In other cases, virtually no residues remain on the surface because they are removed for other purposes, as mentioned previously. Under such conditions, other means of controlling evaporation have been investigated. These generally involved reducing capillary water flow to the soil surface. This can be achieved by tillage at a shallow depth. Such practice is known as dust mulching (also as soil mulching) and is a form of clean tillage.

A dust mulch consists of a zone of loose granular or powdery soil usually produced by tillage or cultivation of the soil at a shallow depth. Dust mulching was shown to be largely ineffective for conserving water under field conditions by the early 1900s (James, 1945) under some conditions. Whereas a dust mulch may reduce evaporation, it usually has not been effective for conserving water in the U.S. Great Plains, where precipitation occurs mainly in summer when the potential for evaporation is greatest. Under such conditions, much of the water was lost by the time tillage could be performed, due to poor soil trafficability, to establish the mulch. When tillage was possible, it exposed moist soil to the at-

mosphere, which often resulted in soil drying to the depth of tillage. Also, tillage was needed to reestablish the mulch after each significant rain, and such frequent tillage resulted in bare soil that was highly susceptible to erosion (Jacks et al., 1955).

Although dust mulching is not an effective practice under the conditions given above, it can be effective for conserving water under some conditions. Where poor trafficability is less of a problem, water conservation generally was greater with a dust mulch in place than from a bare untilled soil by reducing evaporation of water already stored in the soil, but not necessarily greater than with other mulches. Such conditions exist where a distinct rainy season is followed by a distinct dry season, provided soils have adequate storage capacity, or where water moves to the surface from deeper soil layers or a water table (Jalota and Prihar, 1990; Papendick et al., 1973; Papendick and Miller, 1977).

Weed Management

Importance of Weed Control

Water conservation is essential for dryland crop production. It is, therefore, imperative that soil water use by weeds be avoided or minimized to obtain optimum soil water storage at crop planting time. Weeds present before planting decrease the soil water supply for later use by the crop and those present during the growing season compete directly with crops for soil water, space, light, and nutrients.

Weeds use water that could be used by the following crop, which usually reduces yield of the crop. However, where residue production by a crop is low, as may be the case for dryland crops under some conditions, allowing weeds to grow after harvest of a crop can provide erosion control benefits. To minimize water use by such weeds, they should be controlled when sufficient growth has occurred to provide the erosion control benefits (Schillinger and Young, 2000).

Control Methods

Weed control usually is obtained by tillage alone, herbicides alone, or a combination of the two methods. However, hand weeding is done under some conditions. Also, the severity of some weed problems is reduced by using crop rotations (Wiese, 1983).

Regardless of control method used, timely control is essential because weeds may use as much as 5 mm of water from the soil each day (Wicks and Smika, 1973). When tillage is used, a balance is needed between water use by developing weeds and that lost due to exposing moist soil to the atmosphere. Because water loss after each tillage operation may amount to 5 to 8 mm (Good and Smika, 1978), tillage usually can be delayed until the weeds use as much or slightly more water than that which would be lost due to evaporation from the tilled soil. Delaying tillage also reduces production costs and saves energy (Lavake and Wiese, 1979). Although tillage can be delayed to some extent, several operations may be needed to keep weeds under control, thereby conserving water for crop use (Pressland and Batianoff, 1976).

Hand weeding is commonly practiced by small-scale farmers in many countries such as those in sub-Saharan Africa (Twomlow et al., 1997). As with tillage, repeated weeding by hand may be needed. In Zimbabwe, for example, water-use efficiency and grain yields were greater when weeding for corn was at 2, 4, and 6 wk after emergence than with a single weeding at 2 wk after emergence. The soil was driest and yields were lowest when weeds were not controlled.

An advantage of using tillage or hand weeding to control weeds is that transpiration by weeds stops immediately, which is not the case when some herbicides are applied to established weeds. Small weeds generally are easier to control with herbicides than large weeds (Wiese et al., 1966). Large weeds may be especially difficult to control when they are stressed for water, which sometimes is the case under dryland conditions. Development through genetic engineering of crops resistant to some herbicides has greatly expanded the opportunity of using highly-effective, quick-acting herbicides to control problem weeds in the case of many crops, for example, the development of glyphosate resistance in cultivars of soybean [*Glycine max* (L.) Merr.], corn, and canola (*Brassica napus* L.) (Moll, 1997; Padgette et al., 1995; Rasche and Gadsby, 1997). Also, development of crops that are not genetically modified, but which can tolerate certain herbicides, makes it possible to control some weeds and thereby improve crop productivity (Anon., 2002).

Some herbicides prevent weed seed germination and, therefore, avoid soil water losses due to transpiration by weeds. Use of such herbicides, however, may not prevent the germination of seeds of all weed species, which then may become a problem in the planted crop. Also, the herbicide may prevent germination of the crop being grown. Under such conditions, using "safener-treated" crop seed (seed treated to prevent action of the herbicide) has made more effective weed control possible when some herbicides are used (Jones and Popham, 1997).

Cover crops often are grown to protect the soil against erosion, especially in places where residues production is low and adequate water for such crop is available. Cover crops generally have no direct economic value. While such crops generally are not considered to be weeds, their effect on soil water conservation is essentially the same as the effect of weeds. Cover crops may prevent soil erosion, improve infiltration, maintain and increase organic C levels, and possibly improve soil productivity, but they also use water. Depending on soil, environmental, and other conditions, water use by cover crops generally had little or no effect on the water supply for the next crop in humid or subhumid regions when precipitation was adequate. Growing of cover crops, however, generally decreases the water supply for the next crop under dryland conditions in semiarid regions such as the U.S. southern Great Plains. As a result, use of cover crops usually is not recommended in such regions (Unger and Vigil, 1998) because the water supply for and yield of the following crop generally are reduced. An exception may be the strip tillage system used by 20% of the cotton growers in the Southern High Plains in Texas. In that region, which is prone to wind erosion because of high prevailing winds and low canopy cover afforded by cotton, wheat is grown as a cover crop, then chemically terminated before planting cotton. Lascano et al. (1994) found similar evapotranspiration with the strip tillage and a conventional tillage system, and greater partitioning of evapotranspiration to transpira-

tion with the strip tillage system. The cover crop is killed before wheat has high demand for water, and the resulting residues serve to reduce evaporation from the soil surface (Lascano et al., 1994).

Deep Percolation Management

Deep percolation occurs when the amount of infiltrated water exceeds a soil's water storage capacity, through preferential flow, or when water penetrates to depths beyond crop rooting depths and, therefore, cannot be extracted by them. Some nutrients may also be moved by the water to beyond the crop rooting depth (Eck and Jones, 1992), thus resulting in inefficient use of applied nutrients and possibly polluting underground water supplies (Unger et al., 1998).

To reduce the potential for percolation losses of water, crops should be grown that have growing seasons that closely match the season when the potential for percolation is greatest. The potential for deep percolation can also be reduced by management methods that encourage deeper plant rooting, including deep tillage, planting deep-rooting crops, or crop cultivars that extract water from deeper in the soil profile, and adequate fertilization for proper root propagation. Other practices to control deep percolation include bringing materials to the surface that retain more water by deeply plowing the soil, installing subsurface barriers, and adding organic matter to increase the water-holding capacity.

Deep plowing is an expensive operation and its potential benefits relative to the cost of the operation must be carefully considered. Freeman silt loam (fine, mixed, mesic Mollic Haploxeralf) in eastern Washington and northern Idaho has a silt loam A horizon about 30-cm thick overlying a well-developed A2 horizon at the 30- to 46-cm depth. The latter overlies a dense silty clay loam B horizon. Loosening and mixing the B horizon increased plant root proliferation and soil water extraction in the deeper depths (Cary et al., 1967; Mech et al., 1967). When the soil was moldboard plowed 90-cm deep, clayey material from the subsoil was deposited on the soil surface. As a result, 53 mm more water from precipitation was stored in the upper 90 cm of the profile than in conventionally-plowed soil. Mech et al. (1967) hypothesized that water entering the conventionally-plowed soil may have been lost due to seepage along the A2 horizon. The plant-available water-holding capacity in the upper 30 cm of Hezel soil (sandy over loamy, mixed, nonacid, mesic Xeric Torriothent) in central Washington was increased from 36 to 61 mm due to moldboard plowing to a depth of 1 m (Miller and Aarstad, 1972). Sand content of the surface horizon was about 70% before plowing and 40 to 50% after plowing. Greater water retention increased or had potential for increasing crop yields.

Asphalt barriers installed at about a 60-cm depth generally resulted in reduced deep percolation of water and generally increased crop yields in sandy soils (Erickson et al., 1968; Robertson et al., 1973; Saxena et al., 1969, 1971, 1973). The barriers increased the efficiency of rains on the well-drained sandy soils.

Adding organic matter to soils has resulted in variable effects on soil water retention and, therefore, deep percolation. Jamison (1953) found a high positive correlation between soil water retention and organic matter content for sandy soils that have <15% clay, apparently because organic materials retain more water

than sandy soils. In contrast, adding organic materials had no effect on the water-holding capacity of degraded sandy soils in Senegal (Cisse and Vachaud, 1988). Root development, however, was improved, which improved water and nutrient absorption and, therefore, crop yields. Water retention by fine-textured soils and organic materials is similar. Therefore, adding organic matter to fine-textured soils apparently would have little effect on water retention. It could, however, improve soil structure that may increase root proliferation and, thereby, decrease deep percolation. Although adding organic materials to soils has potential for improving water retention, improving soil structure, and/or improving plant root proliferation and, therefore, reducing deep percolation, such improvements under dryland conditions are difficult to achieve because of the generally low amounts of residues (organic materials) produced by dryland crops. Any improvements in soil structural conditions, however, should be beneficial with regard to water infiltration, retention, and use by crops, even under dryland conditions.

CROPPING SYSTEMS AND EFFICIENT WATER USE

The specific practices with which individual pastures and fields within a farm are managed, including tillage, rotation of field crops, nutrient addition, etc., constitute a cropping system. A cropping system is part of a larger farming system, which is a combination of principal crops, animals, and management practices selected by farmers based on such factors as costs of production, soil characteristics, market conditions, and tradition (Loomis and Connor, 1992). The fundamental unit of a farming system is, of course, the farm, which is a goal-oriented system in which specific goals dictate how capital and labor are applied toward production activities.

Efficient water use per se is seldom the farmer's overriding goal. In developed countries, profit and, to a certain extent, maintenance of lifestyle are important goals. In less developed countries, subsistence tends to be a more important goal. For almost all dryland farmers, risk management is an important goal, but acceptable levels of risk differ widely among them. As well as water, the dryland farmer must manage capital, labor, machinery, and time; these may be more limiting to production than water even under dryland conditions. Most dryland farmers (and, where credit is available, their bankers) are also concerned with such goals as stability and sustainability of production, because these facilitate economic planning.

Relations Between Water Use and Crop Growth and Production

Concepts and definitions

Scientists have long been interested in the amount of water required by crops (Briggs and Shantz, 1913; de Wit, 1958; Lawes, 1850; Tanner and Sinclair, 1983). The ratio of production to water use has been termed "water-use efficiency" (WUE), but production can be defined as the amount of marketable yield, total or aboveground biomass, carbon dioxide (CO_2) fixed, etc. Similarly, water use can be defined in terms of applied irrigation water, plant or leaf transpiration, or

the sum of transpiration (T) and evaporation from the soil surface (E). This sum, ET, has been termed "evapotranspiration" (Palmer and Havens, 1958; Thornthwaite, 1948) and "total evaporation" (Monteith, 1981; Penman, 1948).

Because of its different definitions, ambiguity surrounds the term WUE. Gregory (1988) argued that, strictly speaking, the ratio of growth to water use is not an efficiency at all, since it lacks a theoretical maximum value.

Here, we adopt Tanner and Sinclair's (1983) terminology: Any management practice that increases the amount of water available for crop production such as improved capture or retention of water, constitutes an efficient use of water. We define WUE_{ET} as the ratio of yield (Y) or biomass [dry matter (DM)] production to ET, and WUE_T as the ratio of Y or DM to transpiration (T). Other WUE definitions designed for use in irrigated agriculture were discussed by Howell (2001).

The ratio, WUE_T, may be viewed as an index of plant performance. It may include the dry mass of roots and senesced plant parts, and may be determined for only part or all of the growth cycle (Brück et al., 2000; Payne et al., 1992). Studies of crop WUE_T have been commonly conducted in containers to facilitate recovery of roots and prevention of E (de Wit, 1958). On the other hand, WUE_{ET} may be viewed as an index of crop field performance with regard to water use, and is usually expressed as the ratio of Y or aboveground DM to ET (Payne, 1997; Payne et al., 2001). Unfortunately, hydrological processes such as root zone drainage and runoff often are ignored.

Crop Growth, Transpiration, and Water-Use Efficiency (Transpiration Basis)

Due to the simultaneous import of CO_2 and export of water vapor through stomata during photosynthesis, DM is linearly related to T. de Wit (1958) related biomass to transpiration for high radiation environments with the equation

$$DM = mT/E_0, \qquad [3]$$

where m is a crop coefficient and E_0 is mean daily pan evaporation. Since Y can be defined as the product of DM and the harvest index (HI), then Y/HI can be substituted for DM. For reasons reviewed by Tanner and Sinclair (1983), atmospheric water vapor pressure deficit ($e*- e$; $e*$ refers to saturated vapor pressure of air at a given temperature and e is ambient or actual vapor pressure at that temperature) is a better measure of atmospheric evaporative demand than E_0 when relating crop growth to transpiration. Equation [3] can, therefore, be written as

$$Y = mHIT/(e*- e). \qquad [4]$$

We will use this simple equation to consider ways in which WUE and efficient use of water can be improved.

Transpiration. Based on the principle of conservation of mass, any change in the amount of water stored within the crop root zone, ΔS, must equal the difference between any inputs and outputs:

$$\Delta S = \text{Inputs} - \text{Outputs}. \qquad [5]$$

In dryland agriculture, inputs are generally restricted to precipitation (P) and sometimes run-on (R_{on}), while outputs include drainage from the root zone (Q), evaporation from the soil surface (E), run-off (R_{off}) and T. Equation [5] can, therefore, be restated in terms of the processes that determine T:

$$T = (P + R_{on}) - \Delta S - (E + D + R_{off}). \qquad [6]$$

To achieve efficient use of water, the terms on the right side of Eq. [6] must be managed to the fullest extent possible to maximize T. The relative importance of the terms on the right side of Eq. [6], and the degree to which they can be managed, depends on such factors as soil physical and chemical properties, slope, weather patterns, water table depth, landscape position, crops species grown, and availability of inputs. Many of these management options are discussed in the Water Capture and Water Retention sections of this chapter and, for more specific dryland situations in the world, elsewhere in this monograph.

There is, of course, an upper limit for the total amount of T over a cropping season. In general, it is determined under dryland conditions mostly by *P*. But in certain situations, R_{on} (see section on water harvesting) and ΔS (see section on fallowing) can be managed so that T is substantially greater than *P*.

There is also an upper limit to the daily rate of T. Provided there is adequate water in the root zone, the daily rate of T is limited by atmospheric evaporative demand (ETP), commonly quantified by the Penman–Monteith equation (Monteith, 1981), and the crop's evaporative surface, commonly quantified as leaf area index (LAI). Ritchie's (1983) review, which used data for sorghum and cotton, suggests that T/ETP <1 until a LAI of about 3 is reached for a dry soil surface, or an LAI of slightly >5 for a wet soil surface. For pearl millet in West Africa, Wallace et al. (1993) found that T/ETP = 1 at an LAI of about 2, suggesting that the minimal value of LAI required to achieve maximum T varies somewhat with crops and environment. Management of LAI is, therefore, an important way of maximizing T. Of course, under conditions of low water availability, T will be much less than ETP due to a combination of reduced LAI and increased canopy resistance to water vapor diffusion.

Since plant tissue water storage is, in most cases, insignificant in relation to seasonal T, T must be equivalent to the amount of soil water extracted by roots. In many cases, therefore, T can be increased by managing root growth through cultural practices or choice of crop from among or within species. Factors described by Taylor (1983) that affect root water uptake and that may be amenable to management or genetics include root growth rate and duration, root length density, and rooting volume. For many crops, there exists a functional relationship between leaf and root growth (Squire, 1993). Root length and leaf area, for example, differ among species much more than their ratio. Environmental stress, including water shortage, tends to increase this ratio.

The rate of water uptake at the soil/root interface can be affected by both soil and crop properties (Fiscus, 1983), including hydraulic conductivity of the root, hydrostatic pressure potential gradient between the outside and inside of the

root, and the osmotic pressure difference between the outside and inside of the root. The ability of some crop genotypes to lower internal osmotic potential and thereby increase root water uptake and T under water-limited conditions has received much attention in the past (Blum, 1989; Morgan, 1977).

The Coefficient *m*. Field-determined values for the coefficient m of Eq. [4] have been presented by Gregory (1988), Monteith (1988) (his "qD"), and Tanner and Sinclair (1983) (their "field k") for aboveground DM. In general, values ranged from 3 to 4 g kg^{-1} kPa^{-1} for C_3 species and from 8.5 to 10 g kg^{-1} kPa^{-1} for C_4 species. Tanner and Sinclair (1983) and others have concluded that m is largely dependent on photosynthetic pathway (i.e., whether the crop is a C_3 or C_4 species) and is relatively insensitive to the effects of environment and within-species genetics. A large amount of data, however, has also indicated that m is affected by a number of environmental and genetic factors. de Wit (1958) recognized that the value of m was likely to change when much of the DM was produced during periods of partial stomatal closure. Such scenario would occur commonly in many dryland farming systems. For pearl millet, increased m due to restricted water supply has been observed in both container (Brück et al., 2000; Payne et al., 1992) and field (Payne et al., 1995) experiments. Similarly, m has been observed to increase due to water stress in container experiments with sorghum (Onken and Wendt, 1989) and wheat (Parameswaran et al., 1981). Physiological mechanisms that increase m include increased conversion efficiency of photosynthate to biomass because of greater starch production during drought (McCree et al., 1990) and the proportionately greater effect of partial stomatal closure on flux of water (H_2O) compared to that of CO_2 (Nobel, 1999).

There is also ample evidence to suggest that soil nutrient availability affects m. Early on, Viets (1962, p. 229) challenged the notion that the major effect of fertilization was on LAI rather than on photosynthetic efficiency per unit leaf area. Briggs and Shantz (1913, p. 51) explicitly recognized the effect of phosphate on m. Brück et al. (2000) used C isotope discrimination to attribute reduced m of pearl millet during P shortage to CO_2 leakage from the bundle sheath chloroplasts.

Similarly, increased N nutrition has been observed to increase *m* in pearl millet (Boukar et al., 1996), sorghum (Onken and Wendt, 1989), and wheat (Parameswaran et al., 1981). Penning de Vries and Van Keulen (1982) also found that some annual grasses transpire freely, rather than partially close stomata, despite photosynthetic inhibition due to N deficiency. For many species, the rate of photosynthesis is linearly related to leaf N content (Evans, 1993; Nobel, 1999), possibly due to its relation to chlorophyll content (Pham Thi Nhu Nghia et al., 1981).

Because of growing competition for fresh water supplies, whether *m* is under genetic influence is of particular importance to dryland agriculture. A number of studies have demonstrated genetic variability for the ratio of photosynthesis to stomatal conductance within C_3 species, for example, wheat (Farquhar and Richards, 1984), barley (*Hordeum vulgare* L.) (Hubick and Farquhar, 1989), and peanut (*Arachis* sp.) (Hubick, 1990). Many have used C-isotope discrimination as a proxy for this ratio to achieve modest gains in *m* of C_3 species through breeding (Condon and Richards, 1992; Lu et al., 1996; Kirda et al., 1992; Sayre et al., 1995).

There exists genetic variability for C discrimination within C_4 species as well (Hubick et al., 1990), but the utility of C-isotope discrimination as a selection tool seems less likely due to the variation in CO_2 leakage from bundle sheath chloroplasts (Farquhar, 1983). Nonetheless, genetic variation and heritability for the ratio of photosynthesis to stomatal conductance was convincingly demonstrated for sorghum by Kidambi et al. (1990) using gas exchange measurements. Their results are very much in line with data of Onken and Wendt (1989) demonstrating genotypic variation for whole plant m of sorghum.

Theoretically, improvements in m can be effected at the cellular, organ, or whole-plant level (Sinclair et al., 1984). Physiological traits amenable to breeding that influence m include leaf reflectance, glaucousness, pubescence, leaf dimension, cuticular resistance, and leaf-angle distribution (Richards et al., 2002). Many of these also affect aerodynamic transfer of momentum and, therefore, such leaf and canopy boundary conditions as temperature and humidity, which themselves affect the ratio of photosynthesis to transpiration (Nobel, 1999).

Since there exists scope for selection for m, it seems appropriate to reconsider Gregory's (1988) point about WUE_T's theoretical maximum. Boyer (1967) pointed out that the specialized crassulacean acid metabolism (CAM) of pineapple (*Ananas comosus* Merr.) and the genus *Opuntia* permitted DM production comparable to that of sugarcane (*Saccharum* sp.), with five times the WUE_T of any other mesic species. Similarly, Nobel (1999) calculated a ratio of 40 to 56 g CO_2 fixed kg^{-1} H_2O transpired for the desert CAM species *Agave deserti*, compared with a ratio of 6 g CO_2 kg^{-1} H_2O for a C_3 mesophyte.

Such values seem incredible given currently published values for most crop species, but Blum (1988) points out that awns of wheat and barley have transpiration ratios that are several orders of magnitude greater than those of flag leaves or glumes. Among 30 sorghum hybrids measured for leaf gas exchange rates, Kidambi et al. (1990) found that the slope of C assimilation to stomatal conductance of water vapor ranged from 25 to 92 μmol mol^{-1}. Our understanding of genetic control of physiological traits related to m is in its infancy, and the possible use of transgenic material to achieve major gains remains largely unexplored.

We stress that m is a ratio, and that increased DM and Y would not at all necessarily follow from increased m. Partial stomatal closure due to water stress, for example, may slightly increase m, but reduces photosynthesis and, in most cases, growth and yield as well. As discussed in the following section, HI can be adversely affected by environmental factors that might increase m. For many crops, there is a trade-off between yield potential and adaptation to water-deficit (Blum, 1996). Additional potential trade-offs between m and yield are discussed by Evans (1993).

Harvest Index. Were HI of Eq. [4] constant, efficient use of water to maximize Y would largely consist of maximizing T through management of the appropriate terms in Eq. [5]. But HI is determined by a number of complex processes involving assimilate partitioning and plant development, and is, therefore, seldom constant, especially under variable dryland conditions (Jordan, 1983; Kanemasu, 1983).

The historical importance of increased HI to crop improvement has differed among crop species. Evans (1993, 1998) concluded that a close relationship exists

between increases in HI and varietal yield for C_3 cereals such as wheat, barley, oat (*Avena sativa* L.), and rice, especially in high-yielding environments. He attributed about 60% of genetically-obtained yield increases in wheat to increased HI. A similar but less consistent relationship exists between HI and Y for such grain legume crops as soybean, pea (*Pisum* sp.), bean (*Phaseolus* sp.), and peanut. Early and wild cultivars of C_3 cereals and grain legumes tended to have HI values of about 0.2, whereas modern, high-yielding ones have values of about 0.6. For C_4 species such as sorghum, pearl millet [*Pennisetum glaucum* (L.) R. Br.], and corn, however, the contribution of genetic increases in HI to greater yield potential is debatable; Evans (1998) stated that there is little evidence of increased HI or decreased stature in corn.

Because of the diverse environments in which plants grow, and the large range among them for DM partitioning and growth stage duration, it is difficult to draw generalities on the many factors that contribute to partitioning of DM into Y. Squire (1993) stated that partitioning of DM among plant organs is intrinsically very complex, and influenced by environmental, genetic, and cultural factors.

Environmental factors include photoperiod, temperature, nutrients, and the occurrence, timing, and severity of drought. Specific effects of these factors differ among and within crop species. For many crops, HI is conservative unless environmental constraints reduce the number of surviving vegetative reproductive units. Under stressed conditions, partitioning is usually proportional to the size of the sink associated with the reproductive organ (Squire, 1993), which is why HI of many species is particularly sensitive to drought during the reproductive stages (Jordan, 1983; Kanemasu, 1983). In less stressful environments, partitioning depends on determinacy and sink strength. In determinate crops, most assimilate produced during the reproductive growth phase is allocated to the reproductive structure. Among indeterminate crops, partitioning is balanced between the vegetative and reproductive sinks, and the environment can affect that balance (Squire, 1993).

The two main attributes that determine optimum plant population to maximize HI are interception of solar radiation by individual plants, which is governed by leaf area, and the extent to which plants can reduce vegetative mass to allow increased partitioning of DM to Y. Cultural factors that affect HI include fertilizer application and plant population. Corn HI, for example, is particularly sensitive to nutrient availability.

Among cereals and grain legumes, HI begins to increase approximately linearly from zero at the beginning of grain fill until it reaches a cultivar-dependent maximum at maturity. It is, therefore, affected by the relative duration of the vegetative and reproductive growth stages (Evans, 1993), which are themselves cultivar-dependent. In general, DM of early-maturity cereals and legumes is lower than later ones when partitioning to reproductive structures begins, whereas the partitioning of DM to reproductive structures tends to be independent of earliness (Squire, 1993).

Because of the complex effects of environment, cultural practices, and genetic traits related to growth stage duration and growth habits, it is difficult to speculate on the potential for further increases in HI to increase WUE_T. Clearly,

there is an upper limit because some carbohydrates must be partitioned to produce and maintain the photosynthetic apparatus, stems, and roots (Hall, 2001). For wheat, Austin et al. (1980) suggested an upper limit to HI of 0.62, which has already been attained by some modern cultivars. Evans (1993) suggests that it may be difficult to achieve further increases in yield potential by selecting for still greater HI in many C_3 cereals, and states that selection for this trait alone will likely produce inconsistent and possibly disappointing results because of such possible counter-balancing effects as earlier flowering and reduced shoot size. Whether HI can be further increased in C_4 plants and particularly in corn, for example, through reduced stature, merits further investigation.

Vapor Pressure Deficit. Because vapor pressure deficit ($e* - e$) is determined largely by weather, the most practical method for farmers to reduce ($e* - e$) is through the manipulation of planting date (Payne et al., 2001; Richards et al., 2002). Because of the seasonal patterns of ($e* - e$), which is related to temperature, the choice between cool-season and warm-season crops is important (Loomis, 1983). On one hand, cool-season crops, which possess strong growth responses to temperature and the ability to maintain growth despite cool temperatures and low radiation, can achieve substantial increases in WUE because of lower ($e* - e$) (Payne et al., 2001). Warm-season crops, on the other hand, can maintain higher WUE in warm, high-radiation environments than C_3 plants.

Other agronomic practices such as increased planting rates or fertilizer addition to increase foliage production may reduce ($e* - e$) within the crop canopy, and thereby increase WUE_T. Squire (1993) gives examples of effects of climate effects on ($e* - e$) and, therefore, WUE_T using pearl millet in Hyderabad, India, and in the more arid environment of Niamey, Niger. He also cites greater WUE_T of sorghum grown at narrow spacings due to lower ($e* - e$) than at wide spacings in Botswana.

A potential danger with narrower spacings is premature exhaustion of the available water supply before maturity. When water shortage decreases LAI, it often results in increased irradiance of the soil surface, which reduces T and potentially increases E. It also may lead to a "clothesline" effect, that is, a greater rate of transpiration per square area resulting from hot, dry air moving from between rows through plants within rows (Ritchie, 1983; Shuttleworth and Wallace, 1985). This increases ($e* - e$) and thereby can reduce WUE_T.

In some situations, shade can be used to reduce air temperature and thereby reduce ($e* - e$). Some agroforestry systems have been successfully used to effect this (Payne et al., 1998), but care must be taken to reduce competition between crop and tree species for water, nutrients, and other resources.

Crop Production and Water-Use Efficiency (Evapotranspiration Basis)

Although Viets (1962) developed six possible models relating Y to ET and WUE_{ET}, a great many data sets are consistent with his Model B, which depicts a linear relationship between Y and ET (Loomis and Connor, 1992; Payne et al., 2001; Stewart, 1988). Stewart (1988) has, therefore, made the general observation that greatest WUE_{ET} is achieved at greatest yield. A corollary to this observation is that managing and breeding for greater yield generally achieves greater WUE_{ET}.

In Viets' Model B, when Y is sufficiently high, WUE_{ET} asymptotically reaches a limiting value (Ritchie, 1983). However, under dryland conditions, this high level of Y is seldom attained (Payne, 1997; Payne et al., 2001; Stewart, 1988).

There are situations in which Y and ET are not well correlated. Where E constitutes a large or highly variable component of ET, as with sparse-canopied crops, the relationship between Y and ET is not linear (Cissé and Vachaud, 1988; Payne, 1997). Additionally, for crops such as peas that have unstable HI due to high sensitivity to heat (Payne et al., 2001) or other environmental stress, Y and ET are poorly correlated.

One critical component of crop management for optimal WUE_{ET} is plant population. High grain number per area, whether from more ears per unit area or more grains per ear, is a prerequisite for high yield and, therefore, high WUE_{ET}. This has been found for wheat, rice, pearl millet, and sorghum (Evans, 1993). Eastin et al. (1983) point out that seed number per unit land area usually correlates more positively with grain yield than does seed size. Plant population can be suboptimal, allowing ET to be too highly partitioned into E, and thereby WUE_{ET}. It can also be supra-optimal, which may cause the rate of T to be so high that insufficient soil water is available for the crop during sensitive reproductive or grain-filling stages. This reduces yield, and therefore WUE_{ET}. Optimum crop spacing is usually determined by such considerations as rainfall patterns, soil type, crop plasticity (e.g., tillering capacity), and experience (Loomis and Connor, 1992).

Gregory (1988) summarized methods for increasing WUE_{ET} as: (i) reducing E through mulch, modification of plant population and spacing, selecting varieties with rapid early growth, early sowing, and proper fertilizer application; and (ii) increasing water supply to plants through rain harvesting, supplementary irrigation, cultivation to improve infiltration and reduce runoff, weed control, fallowing, application of fertilizer, multiple cropping, and selecting varieties with deeper roots. He reviewed several studies from different parts of the world that have shown increased WUE_{ET} due to fertilizer addition, except in very dry years, with little effect on ET.

Efficient Use of Water in Cropping Systems

Efficient use of water in dryland cropping systems requires the use of appropriate crop sequences for the particular environment to manage crop water use, ensure plant health, and manage risk.

A fundamental strategy of crop choice for a particular dryland cropping system is that its pattern of crop water demand match that of soil water storage and availability. This is illustrated for various cropping systems of India in Table 3–4. Crops with growth cycles that are too long in relation to rainfall patterns or seasonal patterns of water storage usually suffer yield loss because of the onset of drought and unmet water demands of the crop toward the end of the growth cycle. On the other hand, crops with growth cycles that are too short have lower yield because T is less than its potential.

Unfortunately, in most dryland farming systems, rainfall is erratic as well as low. Indeed, rainfall variability often limits yield more than amount per se.

Table 3–4. Change of dryland cropping systems with rainfall amount, growing season length, soil type, and local preferences in India (adapted from Pearson et al., 1995).

Location	Environment	Intercrop system	Seqyebtuak system
Jodhpur	380 mm rainfall, 11 wk growing season, Cambisol soil	Green gram† or cluster bean grown with pearl millet	Pearl millet followed by fallow
Hisar	400 mm rainfall, 13 wk growing season, Cambisol soil	Pearl millet/mung bean or pearl millet/cowpea (for animal fodder	Pearl millet followed by chickpea or mung bean followed by mustard
Hyderabad	770 mm rainfall, 25 wk growing season, deep Vertisol soil	Sorghum/pigeonpea	Sorghum followed by safflower, sorghum followed by chickpea, or corn followed by chickpea
Bangalore	890 mm rainfall, 32 wk growing season, deep Luvisol soil	Finger millet/soybean, peanut/pigeonpea, or finger millet/corn	Cowpea followed by finger millet

† Botanical names are: green gram (or mung bean) [*Vigna radiata* (L.) R. Wilczek], cluster bean (or guar) *Cyamopsis tetragonoloba* (L.) Taub], pearl millet [*Pennisetum glaucum* (L.) R. Br.], cowpea (*Vigna* spp.), chickpea (*Vicia arietinum* L.), mustard (*Brassica* spp.), safflower (*Carthamus tinctorius* L.).

Farmers use a number of strategies suited to their particular setting to cope with rainfall variability. In general, for maximum crop production under variable rainfall environments, drought should be least probable when crop demand and vulnerability are greatest. Sivakumar (1992) used this principle to suggest appropriate maturity groups of pearl millet varieties for different rainfall zones of West Africa, where there is a pronounced north—south gradient for amount and variability of rainfall.

In many developing countries of the tropics, multi-cropping systems, in which two or more crops with different flowering and maturity dates are grown together in the same season, are used as a method of reducing risk of total crop failure. Multi-cropping systems include "intercropping" systems, in which rows of one crop are alternated with those of another; "relay cropping" systems, in which an early-seeded crop is later inter-sown with a second, later-maturing crop; and "alley-cropping" or "agroforestry" systems, in which crop species are grown between woody or tree species. In addition to reducing risk, these cropping systems also improve use of sunlight, water, nutrients, and labor in low-input farming systems. For example, where rainfall patterns or soil texture are such that root zone drainage, or deep percolation, occurs, a legume crop with complimentary rooting patterns might be grown with or after a cereal crop to use water deep in the profile without excessive competition with the cereal (Gregory, 1988). As inputs become more easily available and acceptable risk level increases, crop rotations tend to be more productive and efficient in terms of water use than mixed cropping systems (Loomis and Connor, 1992). Examples of multiple cropping systems from India are given in Table 3–4. Francis (1986) and Willey (1979) have edited excellent texts on the subject of multiple cropping systems.

Risk and Efficient Use of Water

At the beginning of this section, we pointed out that efficient use of water may not be the farmer's over-riding goal, and that all dryland farmers must manage risk. Loomis (1983) pointed out that risk increases as one maximizes use of water in dryland cropping systems because most farmers must manage the water storage term and predict seasonal rainfall. If they choose their cropping systems based on overprediction of rainfall, they will have insufficient water to meet crop water demand, with potentially disastrous results. The acceptable level of risk varies with the individual farming systems, weather, availability of economic support in the event of heavy losses, and individual farmer. A risk-averse cropping system would obtain an acceptable yield level when receiving less than the historical mean amount of rainfall. Subsistence farmers, for example, would want a system that ensured food security even in very dry years. A risk-prone system might be based on the assumption of having 100% or more of soil water and rainfall, and might be driven by potentially large economic opportunity despite occasional years of crop failure. In addition to managing cropping system risk, farmers can manage whole farm risk by animal and forage management, or seeking off-farm employment.

SUMMARY

Dryland agriculture will become increasingly important in our efforts to produce adequate food for an ever-increasing world population because water supplies for expanding irrigated areas for crops are limited and/or being depleted. Also, there is increasing competition for available water supplies among agricultural, urban, industrial, and recreational users. To achieve greater production in the dryland areas of the world, precipitation water must be effectively captured, retained, and efficiently used by the crops. In this chapter, we discussed the principles and practices that should lead to improved production of dryland crops.

The keys to effective water capture are favorable surface conditions for water to readily enter a soil and ample time for infiltration to occur. The most important principle for achieving water entry is protection of the soil surface from raindrop impact energy. Cover provided by growing crops and/or crop residues absorbs raindrop energy, protects soil aggregates, and maximizes surface macropore space, while slowing runoff and thereby increasing water storage in soil for use by a subsequent crop. Tillage methods that retain crop residues on the soil surface are beneficial for increasing water capture because the residues dissipate the energy of raindrops and retard water flow across the surface, thereby providing more time for infiltration. During active plant growth, soil water content is kept low, which further encourages infiltration.

For maximum retention of stored soil water, losses due to evaporation, use by weeds, and deep percolation must be minimized or avoided. Soil water evaporation is a highly complex process that is influenced by soil water potential and temperature gradients and atmospheric conditions; the latter is an inherent char-

acteristic of a given region. Evaporation can be reduced by placing a mulch on the surface to reduce water vapor transfer from the soil to the atmosphere and, in certain regions, by tillage that interrupts water flow in capillaries from deeper in the soil to the surface where it becomes more susceptible to evaporation.

Water use by weeds is wasteful and reduces the amount potentially available for use by crops; they also compete with crops for light, nutrients, and space. Weeds can be controlled by tillage (or hoeing), herbicides, or a combination of those methods. Tillage usually immediately stops water use by weeds, but also exposes moist soil to the atmosphere, which may increase evaporative losses.

Deep percolation can be reduced by growing crops whose growing season coincides with the time when the potential for deep percolation is greatest and by encouraging water use from deeper in the profile (planting deep-rooting crops, deep plowing to remove root growth restricting layers, and adequate fertilization).

Efficient use of water by dryland crops requires appropriate crop sequences suited to the particular environment to manage crop water use, ensure plant health, and manage risk. A fundamental strategy of crop choice for a particular system is that its pattern of crop water demand match that of stored soil water and precipitation availability. Crops with overly-long growth cycles relative to precipitation patterns or soil water availability usually suffer yield loss because of unmet water demands toward the end of the crop's growth cycle. Crops with too-short growth cycles have lower yield because transpiration is less than its potential.

In most dryland environments, rainfall is erratic and low, and rainfall variability often limits yield more than amount per se. Farmers use a number of strategies to cope with rainfall variability. Choice of crops grown and maturity groups of cultivars can be used to minimize the potential adverse effects of rainfall amount and variability.

Efficient water use may not be a farmer's over-riding goal, but all dryland farmers must manage risk. Risk increases as water use in dryland systems is maximized because most farmers must base their decisions on stored soil water and a prediction of seasonal rainfall. If they overpredict rainfall, insufficient water to meet the crop's water demand will potentially cause disastrous results. An acceptable risk level varies with the individual farming systems, weather, availability of economic support in the event of heavy losses, and individual farmer. A risk-averse cropping system would be designed around the likelihood of having only a fraction of the historical mean amount of stored soil water or rainfall for crops. A risk-prone system might be based on the assumption of having 100% or more of soil water and rainfall, and might be driven by potentially large economic opportunity.

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